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Acoustic Tests of Industrial
Vehicles International (IVI)
Marine Vibrators

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varies approximately as the ratio of the hydraulic supply pressures. Interaction between two vibrators spaced 12 ft. apart is minimal at least down to 25 Hz. Measured directivity patterns of the two vibrators agreed well with simple theory.

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ACOUSTIC TESTS OF INDUSTRIAL VEHICLES INTERNATIONAL (IVI)
MARINE VIBRATORS

INTRODUCTION

Acoustic tests of two Industrial Vehicles International (IVI) Marine Vibrators (Projectors) were conducted from 11 to 25 January 1988 at the Naval Underwater Systems Center's (NUSC) Seneca Lake facility. This report will focus on such topics as test configuration, instrumentation, test data analysis and theoretical considerations.

The tests were conducted by a team of personnel from NRL-USRD, IVI, and Texas Research Institute (TRI) in addition to the regular NUSC Seneca Lake team. Two projectors were tested. They were not identical. IVI Projector No. 2 had been modified in an attempt to increase its low frequency output. It arrived at Lake Seneca during the second week of tests after being used several months in Europe. Projector No. 1 was initially tested at Lake Seneca in August 1987 and remained under IVI control.

The objectives of the tests were to resolve some performance questions encountered in the August 1987 Projector No. 1 tests, characterize freefield performance of each projector, and measure dual-projector module performance. All objectives were met with the exception of measuring freefield performance of Projector No. 2. It developed a hydraulic leak and the tests were terminated before this measurement could be performed. Projector No. 1 functioned well throughout the tests.

An unplanned result was the development of a phase-method approach to determine relative location of source measurement hydrophones. Consistent and repeatable results were obtained using this method and they correlated well with elementary theoretical considerations.

TEST OBJECTIVES

Final objectives of the January 1988 IVI projector tests were separated into two categories - single projector and dual-projector module.

Single Projector Test Objectives

Several general questions of projector performance were unresolved from the August 1987 tests of Projector No. 1. The other test objectives were to measure the freefield performance of each projector and performance when two projectors were in close proximity to understand better the interactions and dual-projector module results.

The questions that needed to be resolved and the work that needed to be completed from the August 1987 test of Projector No. 1 were:

- o Eliminate discrepancies involved in measuring the source level (SL) of the projector. The SL differed by as much as 3 dB as determined by a hydrophone positioned horizontally and one oriented vertically from the projector.
- o Measure a definitive (consistent and repeatable) SL vs frequency for Projector No. 1 from 25 to 275 Hz. Discrepancies noted above had prevented this.
- o Demonstrate that the new IVI vibration-isolation mounts operate satisfactorily vs depth. The old mounts were ineffective at operating depths greater than 9.1 m (30 ft).
- o Demonstrate that the new air-compensation system functions satisfactorily vs depth. The old system required too much time to regulate the internal pressure of the projector.
- o Determine the potential of the IVI harmonic distortion suppression technique. Harmonic distortion was high during the August 1987 tests and no suppression technique was available to use.

The test objectives of characterizing the freefield performance of Projectors 1 and 2, operating alone, were:

- o For a given test configuration, measure the SL vs frequency for hydrophones positioned both horizontally and vertically from the projector.
- o For a given test configuration and with the projector operating at the center frequency of 100 Hz, measure the SL vs azimuth from 0 to 360°.

Dual-Projector Module Test Objectives

Two general objectives of the module tests were to characterize its performance and to determine the mutual interaction effects of the two projectors.

Test objectives of characterizing module performance were:

- o For a given test configuration, measure the SL vs frequency.
- o For a given test configuration, and with the module operating at the center frequency of 100 Hz, measure the SL vs azimuth from 0 to 360° for phase differences of 0° and 90°.

Test objectives of determining mutual interaction effects were:

- o Operate Projector No. 1 with Projector No. 2 charged, but not operating, (charged at system hydraulic pressure with the centering feedback loop and air compensation system functioning but the acoustic piston not driven) and measure the SL vs frequency and the output of the linear variable differential transformer linear voltage displacement transformer (LVDT) of each projector.
- o Operate Projector No. 2 with Projector No. 1 charged, but not operating, and measure the SL vs frequency and the output of the LVDT of each projector.

OPERATION OF IVI MARINE VIBRATOR

An outline of the IVI Marine Vibrator is shown in Fig. 1. It is approximately 1.5 m (61 in.) diameter overall and 0.86 m (34 in.) high and weighs 1860 kg (4100 lb.) in air and 884 kg (1950 lb.) in water. The diameter of the acoustic radiating piston is 1.4 m (56 in.) and its maximum working stroke is 31.8 mm (1.25 in.). The complete unit is submerged in water. The topside power package unit is shown in outline in Fig. 2. Prime power is a Deutz V-10 air-cooled turbocharged diesel that develops 259 kw (347 hp) at 2150 rpm. It drives a Sundstrand 26 hydraulic pump that supplies 454 dm³/min (120 gpm) (at 2100 rpm) of fluid at a system pressure of 20.7 MPa (3000 psi).

Operation of the vibrator may be explained with the aid of Fig. 3. From the pump discharge of the hydraulic power package, fluid goes through desurgers and enters the three-stage servo valve at a pressure of 20.7 MPa (3000 psi). The servo valve is electrically controlled from the surface and yields a fluid flow that is proportional to an electrical signal. Servo valve operation is nonlinear, so an LVDT displacement sensor is provided in a feedback control loop of the control electronics. Hydraulic fluid from the servo valve goes to one side of the piston surface in a so-called hydraulic ram cavity (not shown). Pressure generated in this cavity forces the acoustic piston in one direction. The direction of motion is reversed when the pressurized cavity is depressurized and the other side of the ram cavity is pressurized. In this manner, acoustic piston motion follows the controlling hydraulic drive from the servo valve. The acoustic piston performance is also nonlinear so another LVDT displacement sensor is attached to it. The LVDT signal provides feedback to the control electronics to keep the projector centered about the working stroke of the piston.

Space between the back of the acoustic piston and its housing (or frame) is pressurized with air to the local hydrostatic pressure. A circular rolling seal diaphragm isolates the space from the surrounding water. The frame of the vibrator is mechanically isolated from the structure holding it from the surface.

A nearfield hydrophone is mounted near the acoustic piston. In its normal use in marine seismic exploration it is used in a feedback loop to maintain a constant phase relationship between the output of the projector and a desired reference or output signal. In seismic use, all vibrators are operated in phase. In the January 1988 tests, the hydrophone was active but its signal was not used in a feedback loop. Such feedback would have conflicted with the test objectives concerning mutual interaction effects.

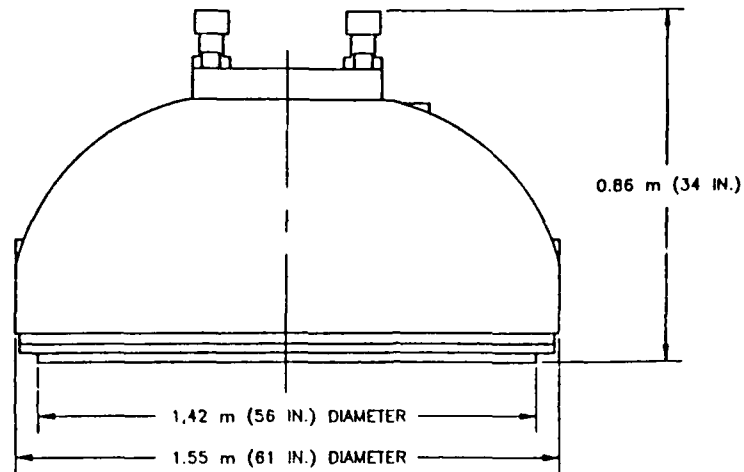


Fig. 1 - Outline of IVI projector.

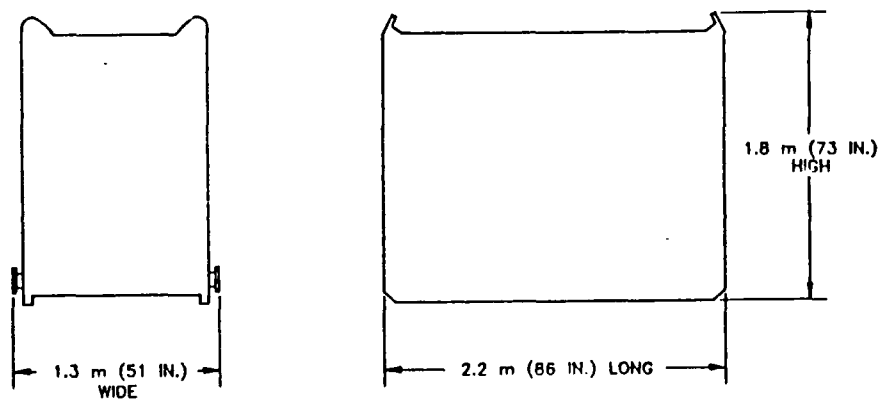


Fig. 2 - Outline of IVI projector power package.

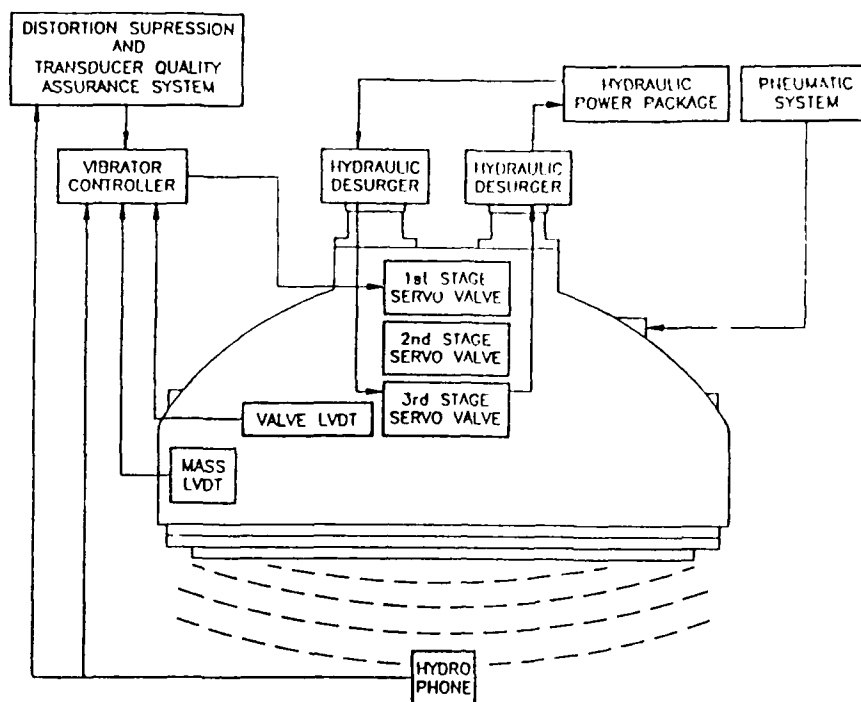


Fig. 3 - Control and power network for IVI projector.

TEST SETUP AND PROCEDURE

Two test setups were used; Projector No. 1 was tested alone at two depths -- 34.4 m (113 ft) and 77.1 m (253 ft), and Projectors No. 1 and No. 2 were mounted on a spreader bar with their acoustic centers 3.60 m (11.8 ft) apart ($\lambda/4$ at 100 Hz) and tested at a depth of 28 m (93 ft).

The two test setups are discussed first followed by the test procedure. During an early stage of these tests, a "phase-method" approach of accurately positioning hydrophones from the acoustic center of the projector was developed. Such an approach had not previously been employed at the Lake Seneca test facility. Therefore, the phase-method approach will be explained in some detail.

Projector No. 1 Test Setup

The test setup for Projector No. 1 is shown in Fig. 4. Identical setups were used at both test depths of 34.4 m (113 ft) and 77.1 m (253 ft). Four NRL-USRD type F37 calibrated hydrophones were used in the tests of Projector No. 1. Hydrophone serial numbers A86, A58 and A66, were calibrated at approximately the test conditions experienced, notably 7°C; hydrophone A3 was calibrated at 19°C and its sensitivity extrapolated to 7°C. The two hydrophones (A66 and A3) below the projector were suspended from a rope cradle attached to, and isolated from, the top (or frame) side of the projector. The distances from the acoustic piston face to hydrophones A66 and A3 were measured while the projector was suspended in air by the crane before deployment. These distances remain unchanged throughout the test. The horizontal distances between hydrophones A86 and A58 and the center line of the projector were measured at their suspension

points on the barge. These distances were subject to small variations throughout the tests due to weather conditions. An uncalibrated nearfield hydrophone was mounted on the frame as shown.

Two digital signal analyzers, each with dual channels, were the primary means of recording data. A schematic of the test setup is shown in Fig. 5. Channels A and B of Analyzer No. 1 were usually used to record the output of two of the four hydrophones in the setup. Output of each of the two hydrophones was fed to a 10-dB preamplifier through a 600-Hz low-pass filter and to the input of the signal analyzer. The signals were monitored with a scope. The output display scales of the analyzer could be adjusted for ease of interpreting the data. Data of the two hydrophones were displayed on two sheets of paper. On the first sheet, the spectrum of each hydrophone was plotted separately and identified as Channels A and B. Frequency scale was either 25 to 225 Hz or 75 to 275 Hz. Full-scale reference dB and dB per division were adjustable for each channel. On the other sheet of data was two spectral plots. One plot was the difference in amplitude of Channels A and B, and the other plot was the phase difference of the two channels (hydrophone signals).

The other analyzer (No. 2) was used to record various combinations of drive signals, nearfield hydrophone and mass LVDT signals. An example is the drive signal (to the vibrator) in Channel A and the mass LVDT (from the vibrator) in Channel B. The two sheets of display for this analyzer usually were similar to those of Analyzer No. 1; i.e., spectra of Channels A and B signals on one sheet and differences of amplitude and phase of the two channels on the other sheet.

Gain of each channel was determined by a Fluke Thermal rms Digital Voltmeter (Model 856H). Gain of each channel was calibrated as 10.2 dbv \pm 0.1 dB over the frequency band 25 to 275 Hz.

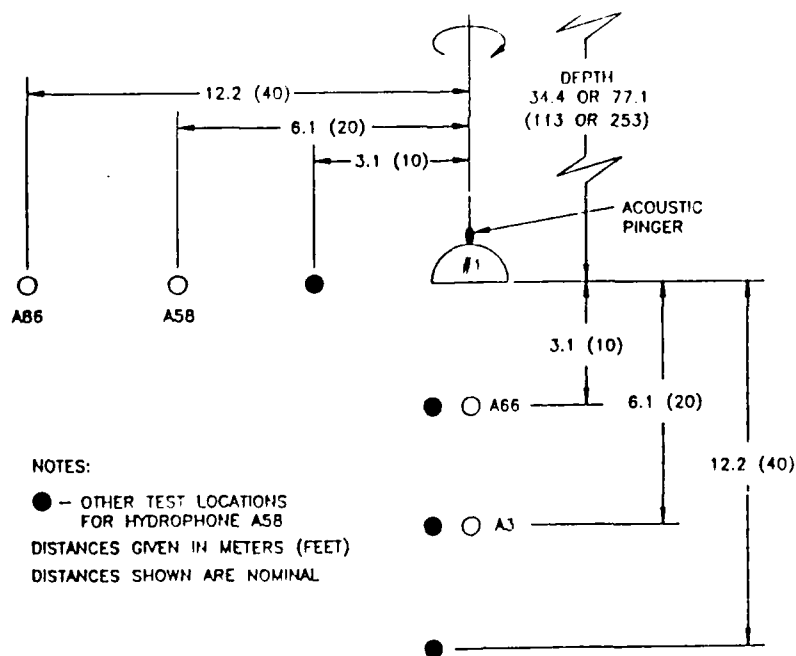


Fig. 4 - Test setup for Projector No. 1.

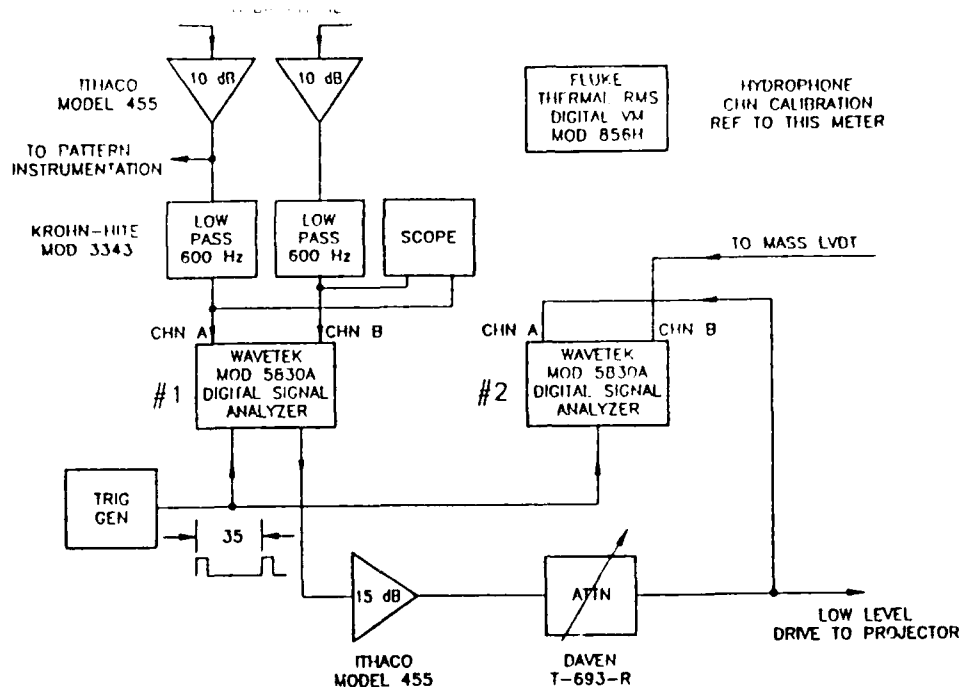


Fig. 5 - Schematic of recording system

Dual-Projector Module Test Setup

Projectors No. 1 and No. 2 were mounted on a spacer bar with their axes 3.60 m (11.8 ft) apart. The setup is shown in Fig. 6. One setup depth of 28 m (93 ft) was used for these module tests. Three of the calibrated hydrophones used in Projector No. 1 tests were also used in the module tests. They had all been calibrated at test conditions. Hydrophone A66 was suspended, as before, in a rope cradle attached to and isolated from the top side of the projector. Its distance was 12 m (40 ft) from the acoustic piston face and remained unchanged throughout the tests. Hydrophone A58 was located 8.5 m (27.9 ft) from the acoustic center of the module. Hydrophone A86 was positioned at 13 or 22 m (44 or 71 ft) from the module. The two hydrophones were suspended from the barge, their distances to the module were measured topside and small variations in measured distances can be expected because of barge movement in choppy lake surface. The uncalibrated nearfield hydrophone was mounted on the spacer bar equidistant from the projectors. For this setup, Projectors No. 1 and No. 2 remained in the same position; the hydrophones were all positioned endfire (i.e., along the line connecting the centers of the two projectors).

The two digital signal analyzers, used in the Projector No. 1 tests, were again used to record spectral data. Channels A and B of Analyzer No. 1 were usually used to record the output of the two hydrophones positioned horizontally. Displays graphs were again output on two sheets as in the one projector tests.

Analyzer No. 2 was usually used to record the outputs of mass LVDT 1 and mass LVDT 2 in Channels A and B. On some tests, various combinations of the near field hydrophone, LVDTs and drive signals were recorded on Analyzer No. 2. Display outputs were again spectral plots of amplitude of each channel, and amplitude and phase differences of the two signals.

Abbreviated directivity tests were conducted at the conditions shown in Fig. 6. With both projectors vibrating continuously at a center frequency of 100 Hz, the module assembly was rotated slowly about its acoustic center in the horizontal plane. The output of fixed hydrophone A86 was put into Channel A as shown in the schematic in Fig. 7. This is the normally-installed beam pattern instrumentation used at the Lake Seneca facility. A narrow-band 100 Hz hydrophone signal drove the polar plotter.

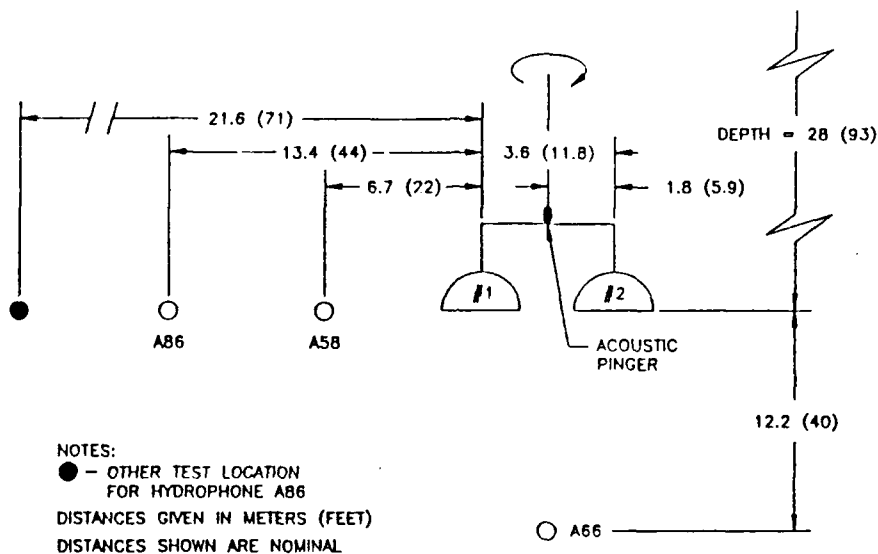


Fig. 6 - Test setup for Projectors No. 1 and 2.

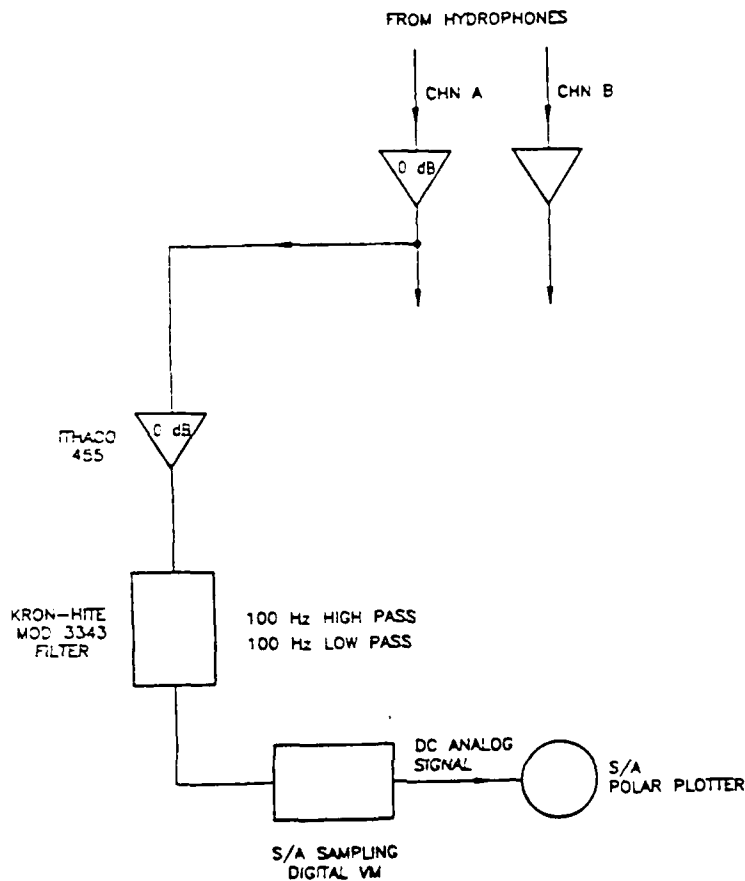


Fig. 7 - Schematic for beam pattern recording.

Test Procedure

After the initial setup of Projector No. 1 at a water depth of 34.4 m (113 ft), as shown in Fig. 4, considerable time was spent developing a test procedure. Of particular note was development of the phase-method approach of accurately determining the relative distances between the acoustic center of the projector and the calibrated hydrophones. This approach is explained in detail in Appendix A. Numerically, if the phase between two hydrophone signals at 200 Hz differs by 1° , then the difference in distances of the two hydrophones from the projector is 21 mm (0.82 in.) where

$$R_i - R_j = \frac{\Delta\theta}{360^\circ} \frac{c}{f} \quad (1)$$

where $R_i - R_j$ is the difference in distances between hydrophones and projector (m); $\Delta\theta$ is the phase difference between hydrophone signals ($^\circ$); c is the sound speed in water (m/s); and f is the frequency (Hz).

The other notable test procedure developed was generating a pseudo-frequency sweep with the vibrator rather than obtaining the data at discrete frequencies.

Time spent developing these procedures greatly enhanced the quality and quantity of data collected.

Single-Projector Test Procedure

Prior to recording the test sequence, four transducers had to be selected for recording two channels for each analyzer. Usually the signal from two hydrophones was fed to Analyzer No. 1, and the drive signal and LVDT signal were fed to Analyzer No. 2.

A typical test sequence involved starting the vibrator at 25 Hz, driving it for three seconds and recording only the last one second for data. The vibrator frequency was increased to 26 Hz, it was operated for three seconds and the last second was recorded. This procedure was repeated Hz-by-Hz up to 225 Hz. Some test sequences covered the range from 75 to 275 Hz. Acquiring data in this manner allowed the analyzers to average a sufficient number of samples of steady state data at each frequency.

Dual-Projector Module Test Procedure

The setup for the module tests was shown in Fig. 6. Prior to lowering the module into the water, the projectors were operated in air at reduced drive signal level. The output of the LVDT of each projector was monitored.

With the module at 28 m (93 ft) depth, Projector No. 1 was operated through a test sequence as described above. In this manner, its performance at this setup can be correlated with its previous single-projector setup. Projector No. 2 was not operated alone.

Projectors No. 1 and No. 2 were operated through a test sequence at various conditions and with various transducers monitored:

- o Projectors No. 1 and No. 2 operated in phase
- o Projectors No. 1 and No. 2 operated 90° out of phase
- o Projector No. 1 operated and Projector No. 2 charged but not operated
- o Projectors No. 1 and No. 2 operated in-phase in the "free running" condition as normally used in seismic exploration

During representative conditions, the flow rate of hydraulic fluid to Projector No. 1 was recorded as a function of frequency. A test sequence was also recorded for Projector No. 1 operated at a system hydraulic pressure of 26.2 MPa (3800 psi).

The final tests involved beam pattern measurements of the module operating at a frequency of 100 Hz with the monitor hydrophone signal recorded through a narrow band filter at 100 Hz. The module was slowly rotated with the module vibrating at 100 Hz. During one test, the projectors were operated in phase. During another test, the two units were operated 90° out of phase.

RESULTS

The principal results are discussed in the sections below. In the first section, resolution of problems encountered in the August 1987 tests of Projector No. 1 are discussed. Definitive freefield performance results of Projector No. 1 are given in the second section. (Performance of Projector No. 2 in the free field was not measured initially because of time constraints and later due to failure of the projector.) Module performance is discussed in the third section. In the last section, general results of the January 1988 tests are discussed.

Resolution of August 1987 Test Problems

An unresolved problem of the August 1987 IVI tests was a 3-dB discrepancy between the SL ($1\mu\text{Pa}$ at 1m) of two measurement hydrophones, one positioned 6.1 m (20 ft) below and the other at 9.1 m (30 ft) off to the side of Projector No. 1 as shown in Fig. 8. These results were supplied by IVI. Part of the discrepancy is attributed to the hydrophone and how it was used. For the August tests, hydrophone F37 (S/N A66) employing a Seneca Lake cable was used at a water temperature (at depth) of -7°C and terminated in the balanced configuration. Subsequent investigation and recalibration found a 1.3 dB discrepancy as follows:

- 0.7 dB Difference in hydrophone sensitivity between 31°C and 7°C ,
(hydrophone A66 had been calibrated at 31°C)
- 0.6 dB Difference due to NUSC & NRL-USRD balanced configuration
calibration
- 1.3 dB TOTAL

The other 1.7 dB was unexplained and may be due to reasons discussed below. An inaccurate value may have been used for the distance between hydrophone A66 and the acoustic center of Projector No. 1 because location of the acoustic center in the vertical plane was unknown. Hydrophone A66 was not mechanically isolated from the housing of Projector No. 1 and may have experienced vertical displacements resulting in an erroneous SL. During the January 1988 tests it was determined, by using the phase-method approach, the acoustic center of the projector was about 0.6 m (2 ft) above the face of the acoustic piston. This accounts for the "3.1 m (10 ft) below" hydrophone SL in Fig. 8 being higher than SL on the hydrophone 6.1 m (20 ft) off to the side. [A detailed discussion of measurement of projector performance at Seneca Lake is covered by Bray and Carson of TRI in a letter trip report dated 9 February 1988.]

In the August 1987 tests, the vibrator was isolated from the structural member holding it to the barge by using air bags as isolation springs. Such springs are effective isolators down to 5 Hz and at shallow depths. The air bags performed well at their design depth of 9.1 m (30 ft), but at greater depths they compressed and provided virtually no structural isolation between the vibrator and barge. Rather than use an air compensation system to operate the air bags at depths greater than 9.1 m (30 ft), IVI replaced the air bags with steel helical springs. These metal springs provided good structural isolation between the vibrator and barge at frequencies greater than 25 Hz.

During the August 1987 tests, the air-compensation system, which equalizes the internal air pressure with the ambient water pressure, took too long to

perform its function. It used a regulator with an air relay to increase the flow. The improved system used in January 1988 was an adjustable sensor mounted on the surface and a large capacity control valve. The internal air pressure could be equalized within 30 s for a 6.1 m (20 ft) depth change. This is considered satisfactory performance.

Harmonic distortion was evident during the August 1987 tests. It was found that driving the vibrator at a given fundamental signal frequency resulted in even-harmonic source levels that were an adequate 20 dB or more below the fundamental SL. However, the odd harmonics, in particular the third, were less than 10 dB down for some fundamental signal frequencies. IVI devised a harmonic reduction routine that reduces the amplitude of the third harmonic. The routine uses the output of the nearfield hydrophone to alter amplitude and phase of the drive signal to reduce the amplitude of the third harmonic. Effectiveness of the reduction system at a fundamental frequency of 80 Hz is shown in Fig. 9. The upper spectrum shows the performance of the vibrator, sensed by hydrophone A58, at 6.1 m (20 ft) distance, operating at 80 Hz, and before harmonic correction was applied. The ratio of the third-harmonic to fundamental is -6.3 dB. The lower spectrum represents identical conditions after the harmonic reduction system was applied. The ratio was decreased to -14.1 dB. Similar results at other frequencies are:

FUNDAMENTAL FREQ (Hz)	RATIO, THIRD-HARMONIC/FUNDAMENTAL (dB)	
	BEFORE CORRECTION	AFTER CORRECTION
120	-17.8	-21.8
90	- 9.6	-19.6
80	- 6.3	-14.1
70	- 6.1	- 9.1
50	- 5.8	-10.6
40	- 8.6	-13.2
35	-10.7	-14.4

There is a definite requirement for the correction; more development is needed to reduce the ratio to at least -15 dB at all frequencies. Being able to utilize the technique with a second pass will help achieve the goal.

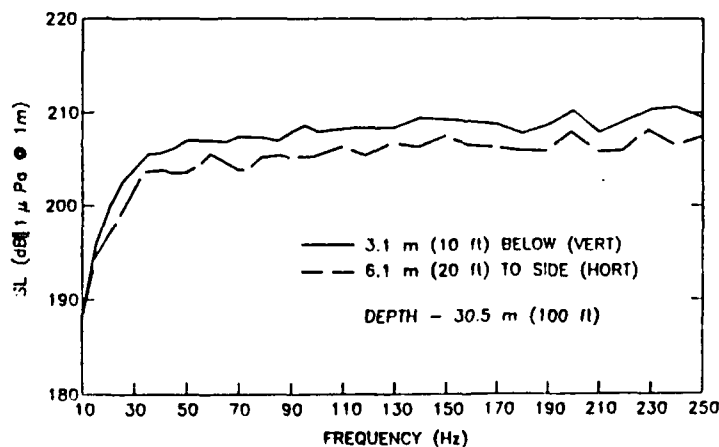


Fig. 8 - August 1987 source level test results of Projector No. 1 (from IVI).

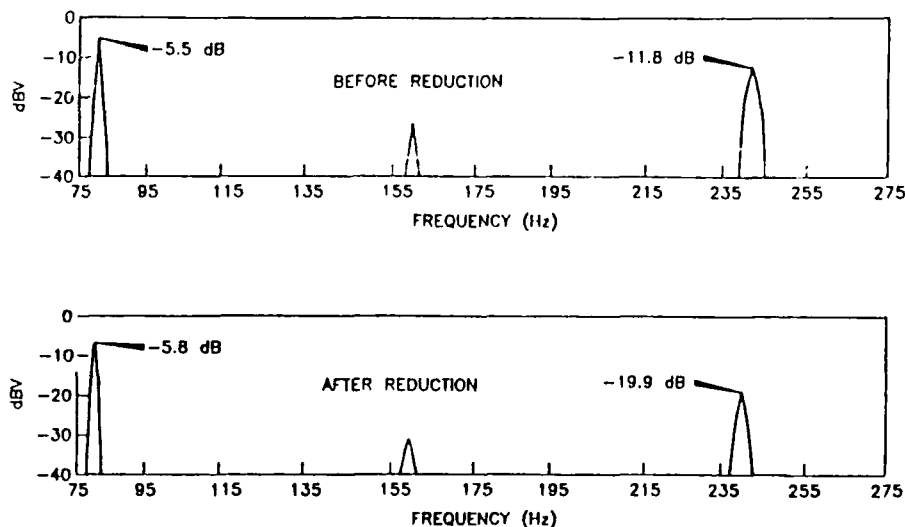


Fig. 9 - Effectiveness of IVI harmonic reduction system.

Projector No. 1 Results

Projector No. 1 was tested in August 1987 and again in January 1988. It is a "standard" unit, has been continuously under IVI control and has been well maintained. Therefore, results presented here for this unit, should be considered representative of IVI projectors. Projector No. 2, on the other hand, had been modified with a larger hydraulic piston and longer stroke to improve its performance at low frequency. It was out of IVI's control for several months prior to the January 1988 tests. A freefield characterization of Projector No. 2 was not done. Failure to characterize Projector No. 2 was due in part to its late arrival from Europe and in part to problems encountered with its operation, as discussed below.

Source Level results given in this report were calculated using the sonar equation:

$$SL \text{ (dB//1}\mu\text{Pa @ 1m)} = V \text{ (dB//V)} - S \text{ (dB//1V/}\mu\text{Pa)} + TL \text{ (dB @ 1m)} - G \text{ (dB)}, \quad (2)$$

where V is the rms voltage level at the spectrum analyzer and annotated on its display; S is the hydrophone freefield voltage sensitivity; TL is the transmission loss to the hydrophone referenced to 1 m; and G is gain of the channel from hydrophone output to analyzer.

An extensive cross checking effort among hydrophones and positions was used to assure sufficient accuracy in determining source level data. The definitive SL spectrum of Projector No. 1 is shown in Fig. 10. Its maximum value is 213 dB re 1 μ Pa at 1m at 175 Hz as sensed by hydrophone A58 located 20 ft. horizontally from the projector, as shown in Fig. 4. Drive signal level of the projector was 10.2 dB which had been experimentally determined to be optimum over the frequency range to 250 Hz. The SL at 45 Hz is 7 dB less and at 250 Hz is 2 dB less than the maximum. At 100 Hz, the SL is 209 dB and at 150 Hz, it is 211 dB. Hydrophone A58 was moved to four other locations, accurately positioned with the

phase-method approach described in Appendix A and a vibrator test sequence recorded. The SL sensed by A58 at the five locations and at various frequencies are:

TEST TJ	DISTANCE m (ft)	SL (dB re 1 μ Pa @ 1m)				
		45 Hz	100 Hz	150 Hz	175 Hz	250 Hz
19-5	6.1 (20) Horizontal	206	209	211	213	211
19-7	3.1 (10) Horizontal		209	211	213	211
20-2	3.1 (10) Vertical		209	210	212	210
20-3	6.1 (20) Vertical	205	208	210	212	210
20-7	12.2 (40) Vertical	205	208	210	212	

These results imply that the vibrator is omnidirectional.

A summary of all data recorded during the Projector No. 1 tests is given in Table B1 of Appendix B.

The ambient noise level at Lake Seneca was measured after the present tests were completed; it is 70-80 dB re 1 μ Pa except at 60 Hz (where it is 130 dB) and 120 Hz (115 dB). The measured spectrum at 30.5 m (100 ft) depth for the conditions noted is shown in Fig. 11.

It is worthwhile to compare the SL as a function of frequency sensed by hydrophones placed in orthogonal horizontal and vertical planes of the acoustic center of the projector and recorded on different days. Three SL comparisons are given in Figs. 12, 13, and 14 to show repeatability of the results from different hydrophones on two days. Figure 12 shows a comparison of tests TJ 19-7 and TJ 20-2. On 19 January 1988 (test TJ 19-7) hydrophone A58 was oriented 3.1 m (10 ft) horizontally (to the side) from the projector and hydrophone A66 was located 3.1 m (10 ft) vertically (below) from the projector. On 20 January 1988 (test TJ 20-2) the locations of the two hydrophones were unchanged. The comparison in Fig. 12 is hydrophone A58 from test TJ 19-7 and hydrophone A66 from test TJ 20-2. The results are within 1 dB - as are the other comparison of test TJ 19-7's hydrophone A66 vs test TJ 20-2's hydrophone A58. The output of each hydrophone repeats from the 19th to 20th. Figure 13 gives similar information except the horizontal and vertical distances from the hydrophones to the projector are now 6.1 m (20 ft). The comparison shown in Fig. 13 is test TJ 19-5 (hydrophone A3) vs test TJ 20-3 (hydrophone A58). Results are again within 1 dB. Comparing test TJ 19-5 (hydrophone A3) with test TJ 20-3 (hydrophone A58) gives similar results. The results of each hydrophone again repeat from the 19th to 20th. Figure 14 shows results for the horizontal and vertical hydrophone-projector distances of 12.2 m (40 ft). These results are test TJ 20-7 with hydrophones A86 and A58 as sensors. These results again are within 1 dB; a similar setup was not tested another day. The above results were presented to emphasize their consistency.

Definitive performance of the IVI standard projector given in Fig. 10 was recorded with a drive signal of 10.2 dBV to the projector. A lower drive signal, 3.1 dBV, was used for some of the tests. The effect of using the lower signal level is shown in Fig. 15; 1-2 dB up to 175 Hz and increasing to 6 dB at 225 Hz.

Comparison of SL vs frequency for a single projector (No. 1) at two different depths is shown in Fig. 16. The 28 m (93 ft) data were recorded with

the module setup (Fig. 6) and the 77.1 m (253 ft) data were recorded with the single projector setup shown in Fig. 4. Maximum difference between the results is 1.2 dB over this depth range of 49.1 m (160 ft) (0.50 MPa or 72 psi hydrostatic pressure difference); the hydraulic supply pressure is 20.7 MPa (3000 psi). The expected reduction of SL is 0.2 dB $[20 \log (3015-72)/3015]$ for a constant hydraulic supply pressure of 20.8 MPa (3015 psia) at depth driving the piston in a 0.50 MPa (72 psi) higher pressure environment. For much greater operating depths the supply pressure sensed at depth needs to be increased (~ 10 kPa/m or 0.45 psi per ft).

The last test conducted was recorded with a hydraulic system pressure of 26.2 MPa (3800 psi). "Normal" system pressure was 20.7 MPa (3000 psi). This comparison is shown in Fig. 17. Improvement in SL is 2 dB across the band from 75-175 Hz; the improvement reduces to 1 dB at 275 Hz. If the hydraulic flow rates at the two pressures remained the same, then the expected increase in SL is 2.1 dB $[20 \log (26.3-0.39)/(20.8-0.39)]$. [Note that 0.39 MPa absolute (56 psia) is the absolute pressure at 28 m (93 ft. depth).]

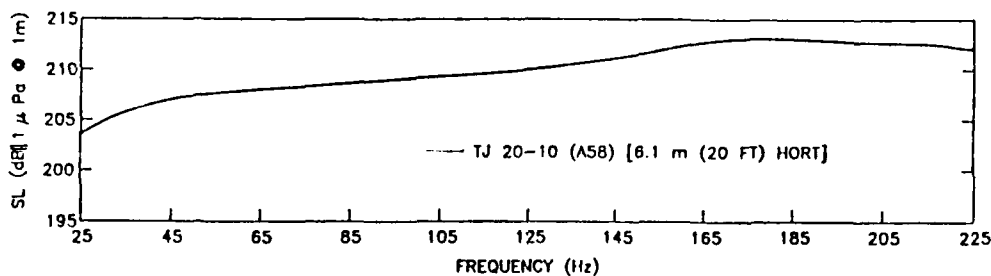


Fig. 10 - Source level of Projector No. 1.

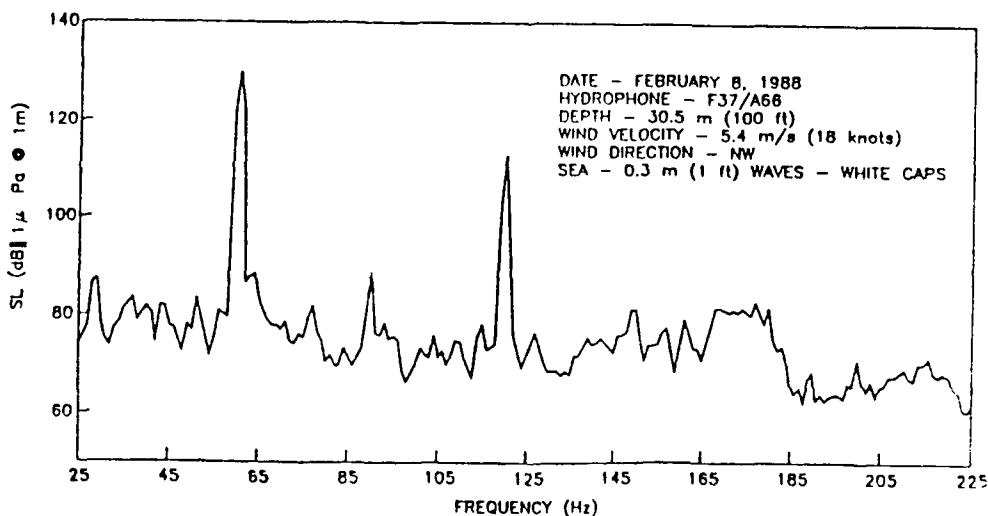


Fig. 11 - Ambient noise level at Lake Seneca Test Facility.

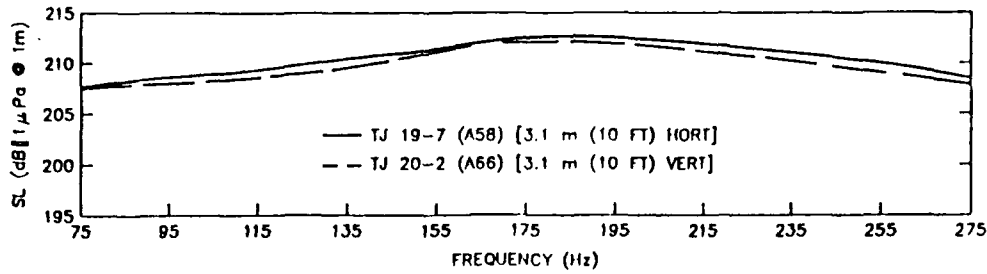


Fig. 12 - Comparison of source level sensed by hydrophone 3.1 m (10 ft) from projector.

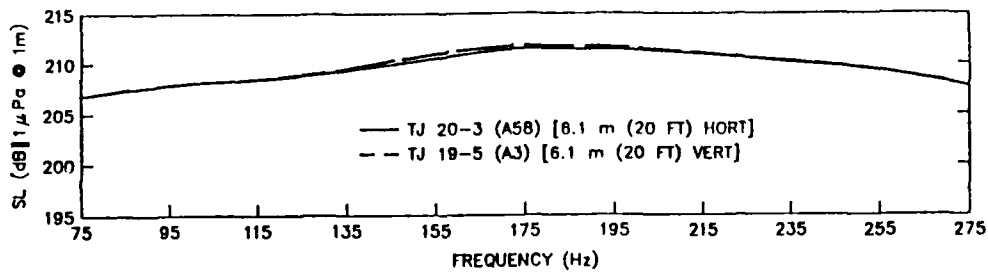


Fig. 13 - Comparison of source level sensed by hydrophone 6.1 m (20 ft) from projector.

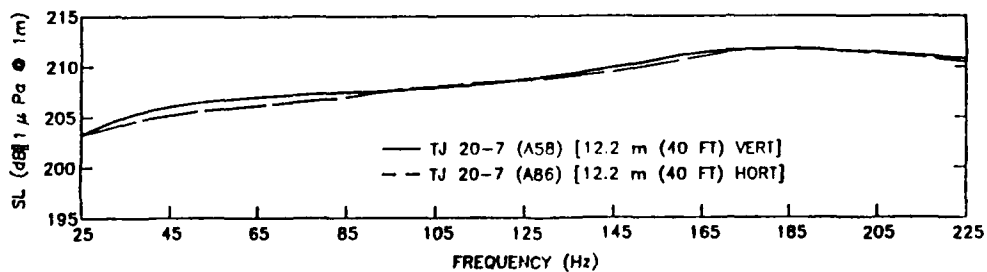


Fig. 14 - Comparison of source level sensed by hydrophone 12.2 m (40 ft) from projector.

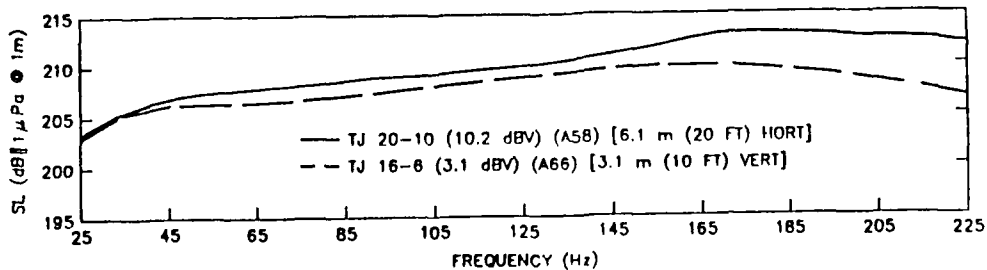


Fig. 15 - Effect of projector drive-signal amplitude on source level.

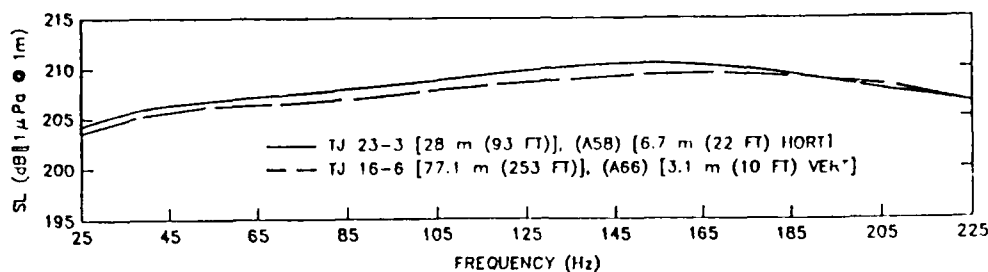


Fig. 16 - Effect of projector depth on source level.

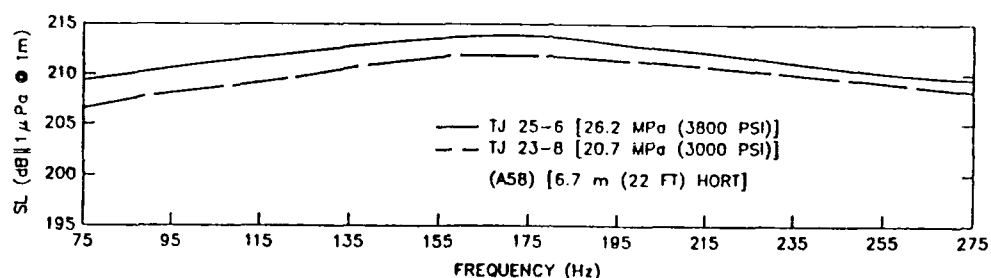


Fig. 17 - Effect of projector hydraulic supply on source level.

Dual-Projector Module Results

Projectors No. 1 and No. 2 were tested as a module, as shown in Fig. 6, at a depth of 28 m (93 ft). Projector No. 1 was tested extensively at depths of 34.4 and 77.1 m (113 and 253 ft, respectively); results were given earlier. Projector No. 2 arrived at the test site late and was not tested alone in the free field. In fact, due to priority of obtaining module test data, Projector No. 2 was not even tested alone in the module configuration. Although it had been modified (larger piston and longer stroke), its SL was approximately 1 dB less than the SL of Projector No. 1 inferred from the pattern results.

Combinations of single-projector test results and the limited Dual-Projector Module test results showed that velocity control for the Dual Projector Module is not a problem. However, IVI Projector No. 1 was not identical to IVI Projector No. 2 and special adjustments were needed to achieve the desired velocities to obtain the broadside and end-fire beam patterns. Specifically, a 20° compensation in the relative phase of the two drive signals was needed in order to achieve the desired phase relation for the actual radiating face velocities. Likewise, for broadside electrical steering a -20° relative phase was used on the drive signals in order to achieve a 0° phase delay between the velocities. The fact that a constant compensating adjustment of -20° worked for all steerings is one of the experimental indications that achieving velocity control of the two projectors of the module is not a problem for a single Dual-Projector Module operating in the free field.

Results of comparing the displacement of the projectors under various conditions are discussed first. The comparisons were made after the voltage

output of each LVDT was divided by the voltage sensitivity of the LVDTs. Sensitivity of L1 (LVDT for Projector No. 1) was 7.0 mV/m (0.275 V/in.); sensitivity of L2 was 12.7 mV/m (0.500 V/in.). It was assumed, cautiously, that the sensitivity was constant over the frequency range tested, 25 to 275 Hz. The next results presented are comparisons of SL for various conditions. Limited, but significant, pattern results obtained before failure of Projector No. 2 are given. Finally, comparison of hydraulic flow rate to Projector No. 1 for various operating conditions are presented.

Figure 18 shows a comparison of the acoustic piston amplitude and phase spectra of the two projectors operating in air. The upper curve shows that the two projectors are essentially in phase up to above 190 Hz where Projector No. 1 begins to lag. This is evident in the lower curve where the amplitude ratio L1/L2 varies from 0 dB at 25 Hz to less than 3 dB at 190 Hz and increases to about 6 dB at 225 Hz. Operation of the projectors in air shows that they are not identical.

Similar but different results of the two projectors operating in water are shown in Fig. 19. The upper curve shows the two projectors are in phase up to 145 Hz where Projector No. 1 lags Projector No. 2. Again, this is evident in the lower curve where the amplitude ratio varies less than 3 dB from 25 to 125 Hz. Beyond 125 Hz the amplitude of Projector No. 1 increases with respect to No. 2.

A direct comparison of the amplitude spectra of Projector No. 1 operating in air and in water is shown in Fig. 20. This comparison shows the effect of water loading vs air loading. At a frequency of 25 Hz the projector probably reaches its maximum stroke in water and, as expected, in air. The amplitudes sensed by the LVDTs are the same at 25 Hz. At higher frequencies, the amplitude of the projector operating in water is less due to higher mass loading of the water.

The last comparison of amplitude spectra of the two projectors is shown in Fig. 21. It is the most meaningful comparison with respect to interaction between the two projectors. Projector No. 1 was operated in the stepped-frequency mode described earlier while Projector No. 2 was charged at system hydraulic pressure with its centering feedback loop and air compensation system operating, but the acoustic piston of Projector No. 2 was not driven. Amplitude of Projector No. 2 is more than 20 dB below the amplitude of Projector No. 1 over most of the frequency band, as shown in Fig. 21. This indicates acoustic interaction between the two projectors is low for these conditions.

The results shown in Fig. 22 compare the performance of a single projector (No. 1) with the module (Nos. 1 and 2) using hydrophone A58. The module results were endfired with a 0° phase difference between Projectors No. 1 and No. 2. As expected, the SL of the module is 6 dB higher than the single projector at low frequency and 3 dB higher at 100 Hz. At higher frequencies the SL of the module is less than the single projector.

The final SL results shown in Fig. 23 compare the module performance (endfire, 0° phase) for the "free-running" and "stepped" frequency modes of operation operating at a 3.1 dBV drive signal level. The normal mode of operation in marine seismic exploration is "free-running," a sweep from 25 to 225 Hz would take about 20 s. The "stepped" frequency mode of operation as

earlier was used during the tests. Data is recorded for 200 s during a stepped sweep from 25 to 225 Hz (1 s per Hz). More energy is radiated because of the time of operation during the tests were longer.

Two measured patterns are shown in Fig. 24; each is compared with its theoretical pattern. One pattern is for 0° phase difference between the two vibrators. The other pattern is for 90° phase difference. Due to time constraints 180° patterns were run; the patterns are approximately symmetrical about the axis of the module. (The relation of the source levels of these two patterns and the front-to-back ratio of the endfire pattern are interpreted as further indirect validation that achieving velocity control is not a problem for the Dual-Projector Module. Note that for 0° phase delay the broadside SL is 3 dB above the SL of the fore- and aft- endfire positions. Also note, for 90° phase delay, the endfire SL is 3 dB above the broadside result.) The Projectors were spaced 3.60 m (11.8 ft) apart ($\lambda/4$ at 100 Hz). The module was operated at 100 Hz and the received signal narrow-band filtered at 100 Hz. Broadside results of the Dual Projector Module show a 6 dB improvement compared with a single projector as expected for 0° phase difference. Endfire results of the module indicate a 6 dB improvement over one projector as expected for 90° phase difference and a front-to-back ratio of about 15 dB. Theoretical patterns, assuming no interaction between projectors, are shown for comparison.

Experimental and theoretical curves are shown in Fig. 25 for a phase difference of 117° between the projectors. Agreement between experiment and theory is very good for all cases.

As a final indication of acoustic interaction between projectors in the module, hydraulic flow rates to Projector No. 1 were measured for various conditions. Only one flow meter was available. The flow rate is given in "counts" where 5 counts are approximately equal to 1 gpm of hydraulic fluid. For all of these tests (except one) the system pressure was held constant at 20.7 MPa 3000 psi and the fluid flow rate varied as a function of frequency. This is analogous to holding the voltage constant with the current varying with frequency. Results in Fig. 26 show the flow rate as a function of frequency for three identical test conditions. These results show repeatability of results in the single projector setup: 10 to 15 counts, 7.6 to 11.4 dm³/min (2 to 3 gpm), or about 5%. In Fig. 27, results are shown for Projector No. 1 in the single projector setup and in the dual projector module setup (both projectors operating). For the module setup, two identical tests were run; below 140 Hz repeatability was better than 1% and above 140 Hz the flow rate was within 5% for the two tests. Comparing single-projector and module results show a higher flow rate to the single projector below 125 Hz by about 10%. Above 125 Hz the flow rate to the single projector is 10% less.

Results given above were for a drive signal level of 10.2 dBV; results in Fig. 28 are for a level of 3.1 dBV. Comparing Figs. 27 and 28 below 125 Hz, flow rates are about the same for the two drive signal levels and above 125 Hz the 10.2 dBV drive signal level requires a greater flow rate. Comparing the single-projector test with the two module test results in Fig. 28 shows the module results bracket the single-projector results; results are all within 10%. The results at higher system hydraulic pressure show a higher flow rate across the frequency band, as expected. Finally, results for the module operated in air show the higher flow rate (vs module in water) because the projector face is more lightly loaded. These hydraulic flow rate results, taken together,

indicate the interaction between the projectors is small (less than about 10% over most of the frequency band from 50 to 200 Hz and about 5% at 100 Hz).

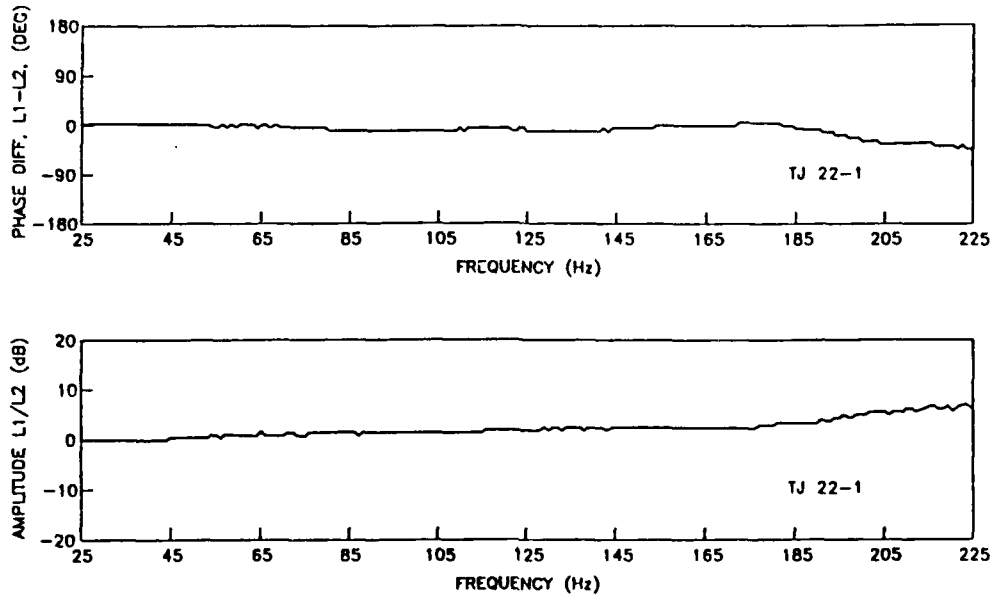


Fig. 18 - Comparison of amplitude and phase of Projectors No. 1 and 2 operating in air.

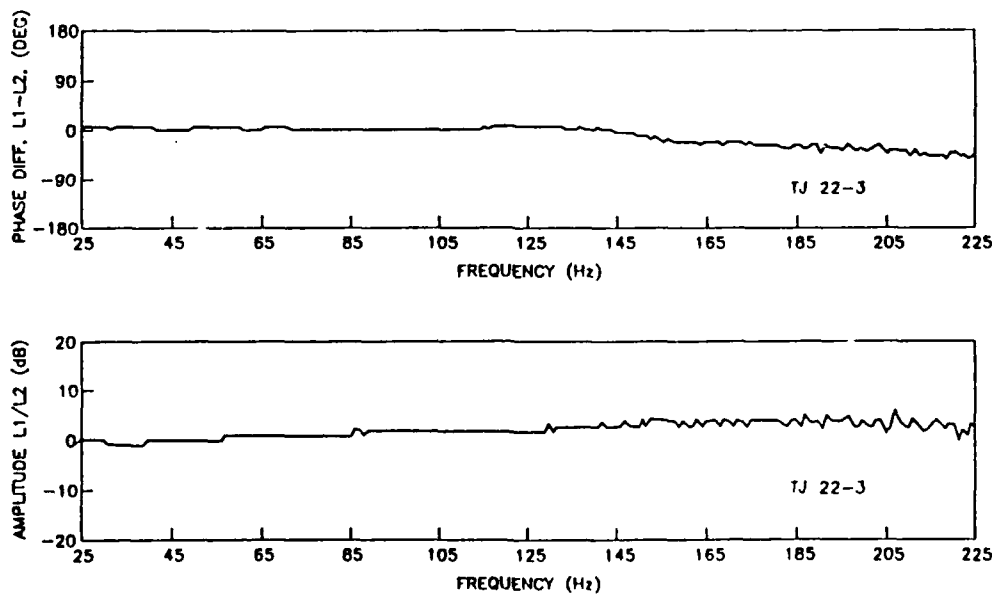


Fig. 19 - Comparison of amplitude and phase of Projectors No. 1 and 2 operating in water.

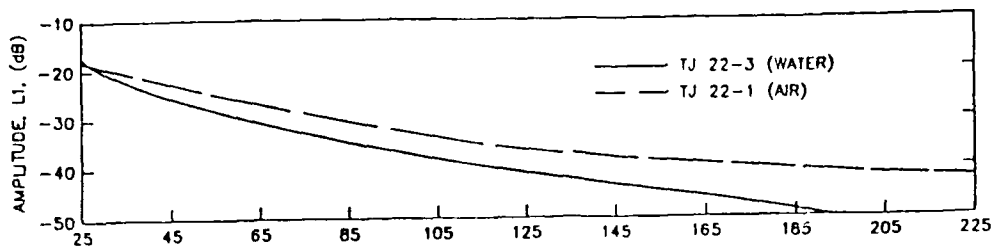


Fig. 20 - Comparison of amplitude of Projector No. 1 operating in air and in water.

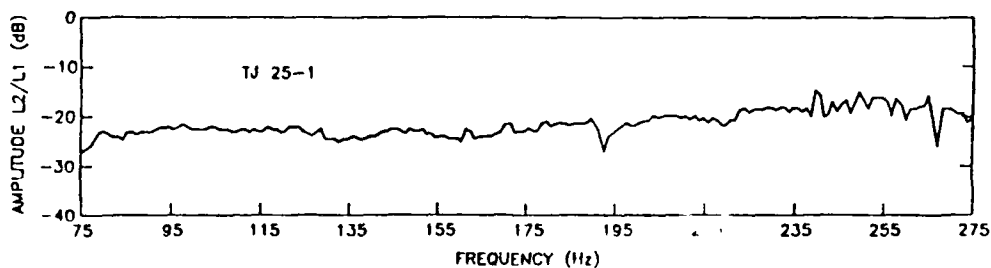
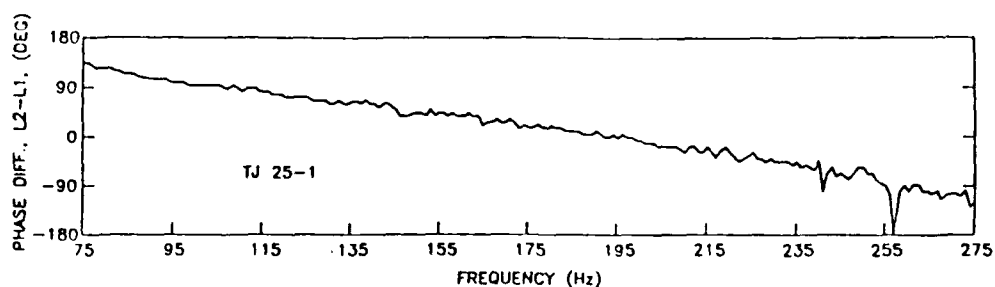


Fig. 21 - Comparison of amplitude and phase of Projector No. 1 operating and Projector No. 2 charged but not operating.

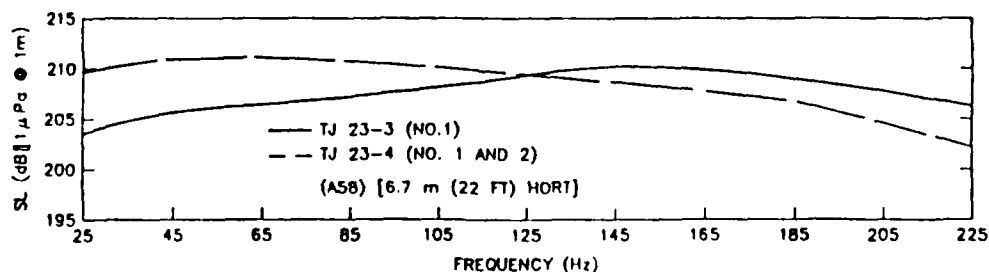


Fig. 22 - Comparison of source level of Projector No. 1 and Projectors No. 1 and 2.

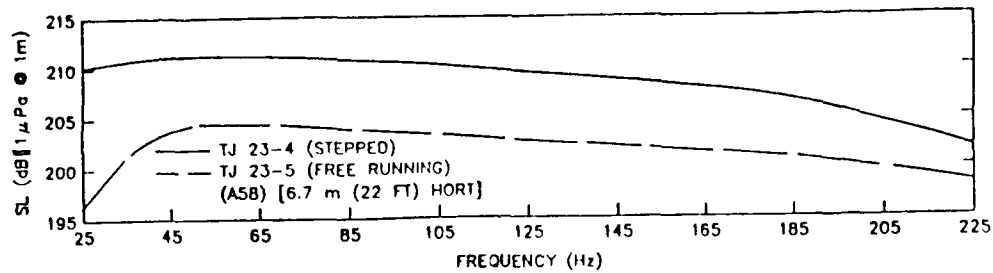


Fig. 23 - Comparison of source level of Projectors No. 1 and 2 (free-running) and Projectors No. 1 and 2 (stepped).

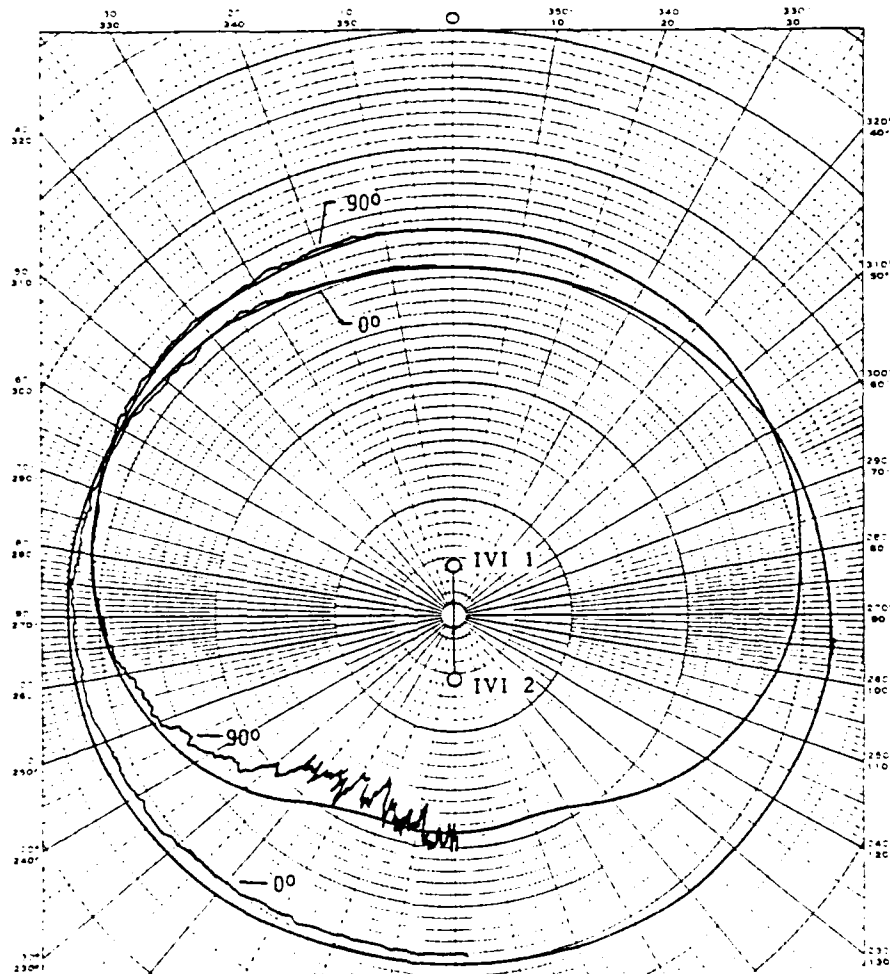


Fig. 24 - Beam patterns at 0° and 90° phase differences (theory vs experiment). Frequency: 100 Hz; Depth: 28 m (93 ft); Drive Signal: 10.2 dBV; System Pressure: 20.7 MPa (3000 psi); (A58) [6.7 m (22 ft) HORT].

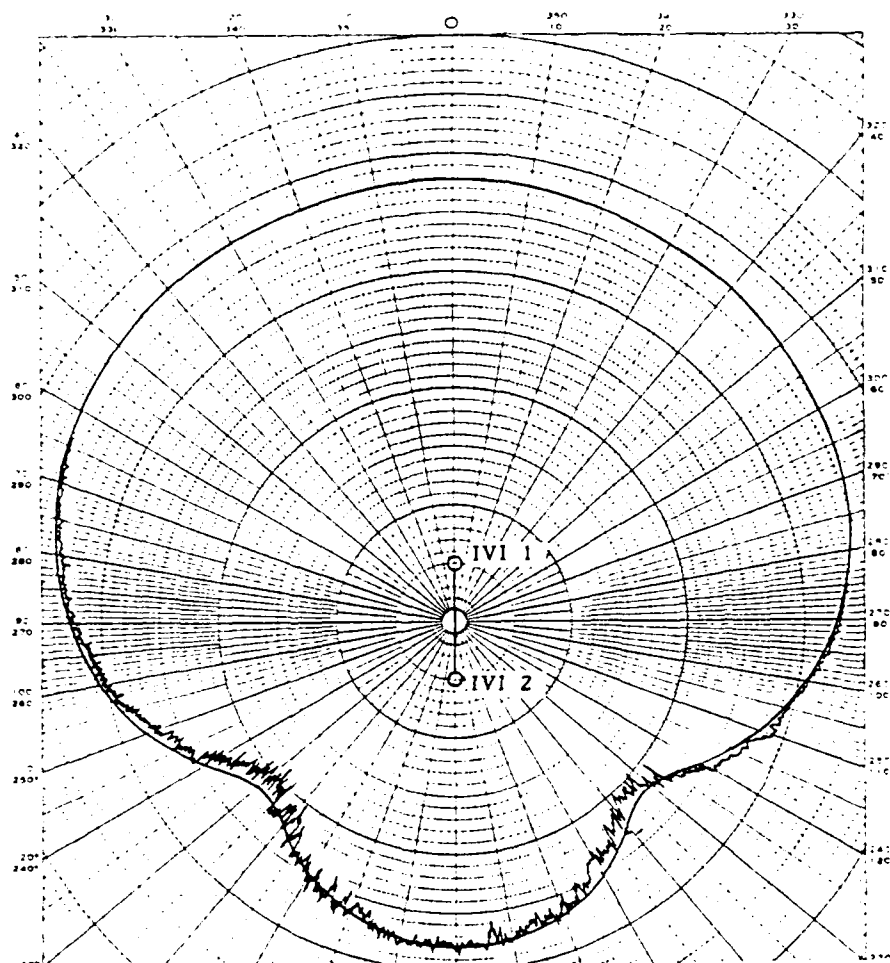


Fig. 25 - Beam pattern at 117° phase difference (theory vs experiment).
 Frequency: 100 Hz; Depth: 28 m (93 ft); Drive Signal: 10.2 dBV;
 System Pressure: 20.7 MPa (3000 psi); (A58) [6.7 m (22 ft) HORT].

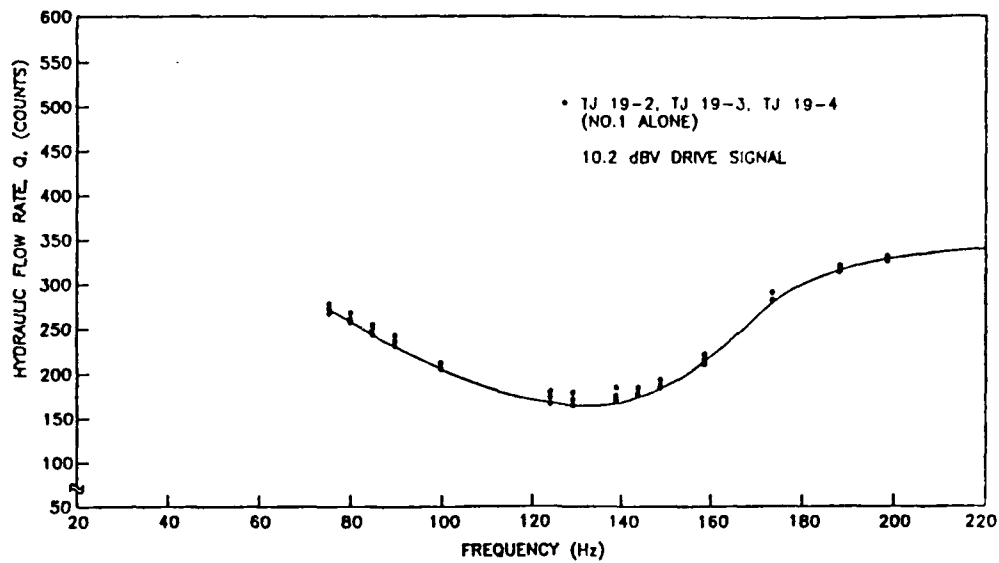


Fig. 26 - Variation of hydraulic flow rate with frequency of a given setup of Projector No. 1.

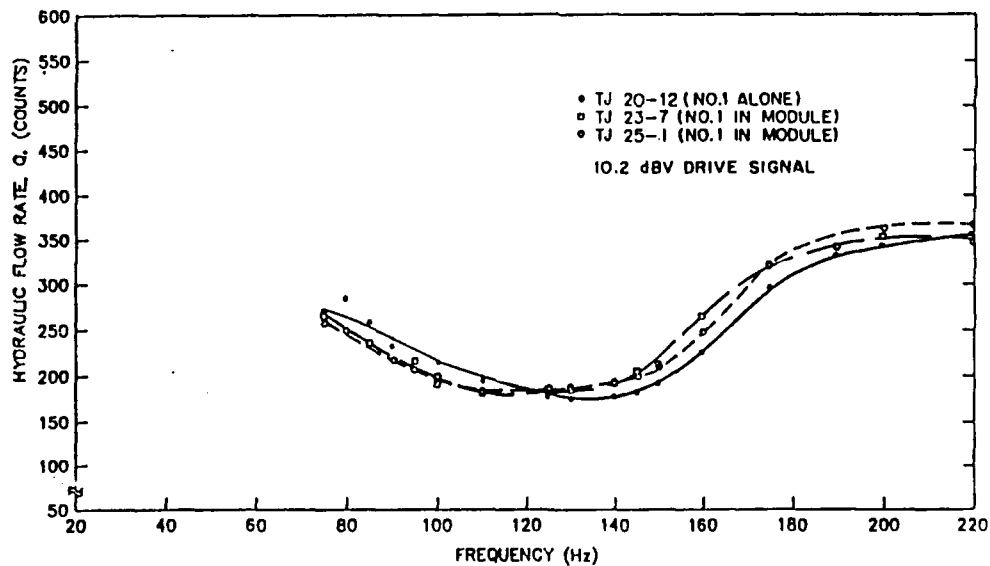


Fig. 27 - Variation of hydraulic flow rate with frequency for Projector No. 1 (alone and in module).

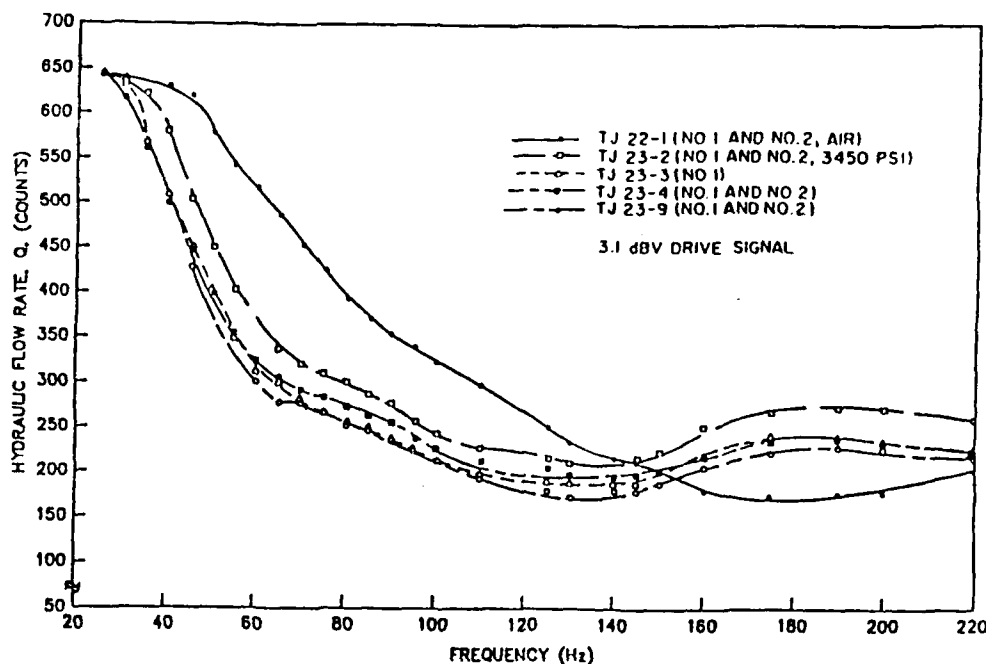


Fig. 28 - Variation of hydraulic flow rate with frequency for Projector No. 1 for various operating conditions.

SUMMARY

Definitive SL vs frequency curve was generated for IVI Projector No. 1 (Fig. 10).

Dual-Projector Module velocity control and other interaction effects caused no problems in operating the IVI Dual-Projector Module from broadside to endfire electrical steered directions. In particular, well-behaved broadside and endfire pressure patterns were produced (Figs. 24 & 25).

IVI harmonic suppression technique was successfully demonstrated (Fig. 9).

Problems encountered with the August 1987 IVI tests were resolved.

ACKNOWLEDGMENTS

The contributions of the following people made this project a success. Mr. Dick Hugus of NRL-USRD and Mr. Dave Carson of Texas Research Institute (TRI) did much of the planning and execution of these tests. Mr. Alan Bray of TRI also helped with the planning. Messrs. Elmo Christensen of IVI and Harry Simon of NUSC's Lake Seneca Facility were invaluable during the test phase. Dr. Robert Timme contributed his insight throughout the work provided much support and encouragement.

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APPENDIX A

PHASE-METHOD APPROACH

This portion was written by Dr. David L. Carson of Texas Research Institute, Inc.

As the January 1988 (the second IVI test) acoustic measurements of IVI projector No. 1 progressed, there was apparently a consistent bias of approximately 1 dB higher source level measured on hydrophones in the horizontal plane (See Fig. A1) vs the source level measured on hydrophones along the vertical axis. This 1 dB difference would have ordinarily been dismissed as experimental error; however, because of the previous 2.5 to 3.0 dB bias discrepancy in the first IVI tests (the August 87 test - note: the bias was in the opposite direction, that is, higher on the vertical hydrophones) between horizontal and vertical hydrophones there was a strong motivation to find a method to demonstrate that this 1 dB bias was indeed measurement error. If it had been possible to run a vertical directivity pattern, this would have been the chosen method. If, as expected, the vertical pattern had been found to be omni, then the bias would have been demonstrated to be due to experimental error.

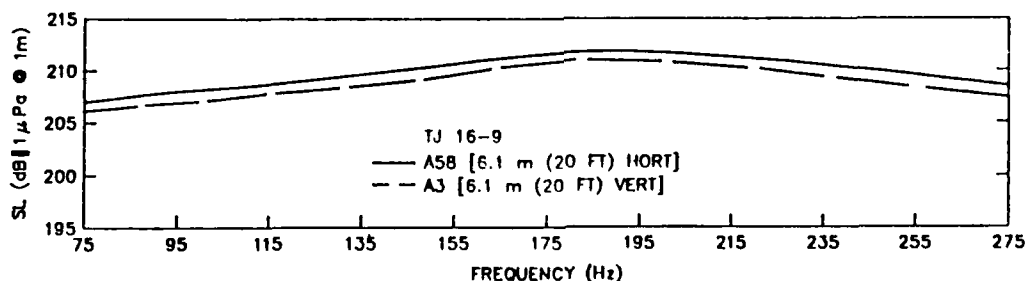


Fig. A1 - Comparison of source level senses by hydrophones in the horizontal and vertical planes of projector (1-dB bias).

Unfortunately, there was no practical way to measure the vertical pattern. (The horizontal pattern was found to be omni in the August 1987 test.) Also, there was the problem of finding the location of the acoustic center along the vertical axis of the IVI projector. Therefore, another method was devised and applied as is described next. In developing the method, it was assumed the projector operated at steady state, the water had a constant sound speed and the location of the acoustic center of the projector was not a function of frequency.

The phase differences, $\Delta\theta_j$ [$(\Delta\theta_{ij} = \theta_i - \theta_j$, see Eq. (A5a)], between the pressure readings at points i and j in Fig. 2A, may be used to adjust the distances R_i and R_j (shown in Fig. A2) from the acoustic center so that $R_i = R_j$. For communication and clarification purposes, the following discussion of this

$\Delta\theta_{ij}$ method of measuring $R_i - R_j$, presents a simple heuristic derivation of Eq. (A1) [or equivalently Eq. (A1a)] of $\Delta\theta_{ij}$ as a function of $R_i - R_j$. After the derivation of Eq. (A1) is presented, the discussion outlines the use made of this $\Delta\theta_{ij}$ method as a technique of demonstrating that the subject bias was indeed experimental error and that the IVI projector is in fact omni in a vertical plane as oriented in Fig. A2. A more general application of the method is also suggested. Instrumentation errors in measuring $\Delta\theta_{ij}$ are temporarily ignored.

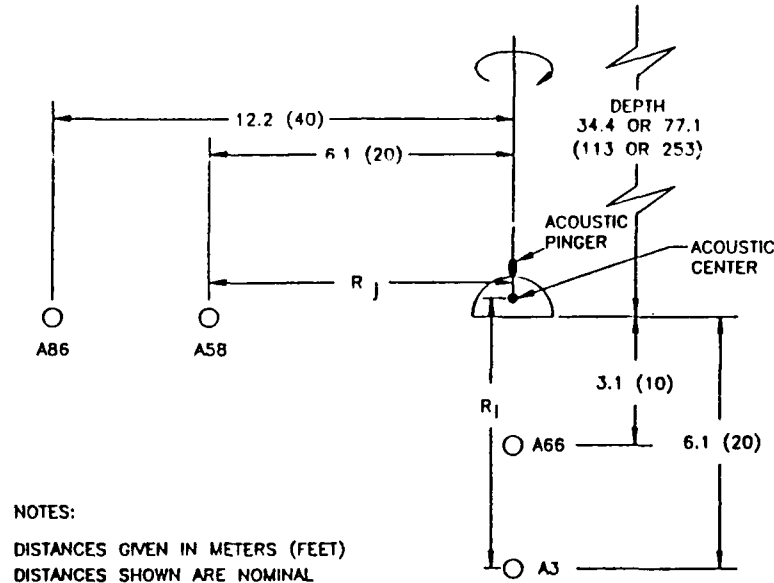


Fig. A2 - Test setup for Projector No. 1.

Referring to Fig. A2, the phase difference, $\Delta\theta_{ij}$, of the phase of the pressure measured at point i minus the phase of the pressure measured at point j is given in radians by Eq. (A1) or in degrees by Eq. (A1a) as follows.

$$\Delta\theta_{ij} = \frac{-2\pi}{c} [R_i - R_j] f \quad (\text{in radians}), \quad (\text{A1})$$

$$\Delta\theta_{ij} = \frac{-360}{c} [R_i - R_j] f \quad (\text{in degrees}). \quad (\text{A1a})$$

In these equations any consistent set of units may be used for the distances R_i and R_j , the speed of sound in water c , and the frequency f .

To derive Eq. (A1), assume that all points of interest, such as i and j of Fig. A2, are in the farfield of the sound projector so that the concept of an acoustic center applies. The acoustic center is that point on or near the sound projector from which the transmitted sound appears to emanate. For definiteness assume that the sinusoidal acoustic signal at a given frequency, f , is referenced to an electrical drive signal, D_r , given by Eq. (A2).

$$D_r = E_o \sin \omega t, \quad (A2)$$

where $\omega = 2\pi f$ and E_o is the magnitude of the drive voltage signal.

At any instant of time, t , the angle $\theta_r(t)$ of this reference signal is given by Eq. (A3).

$$\theta_r(t) = \omega t. \quad (A3)$$

The same signal will have to travel through the electronics hardware, for a time t_{ei} and then through the water to the hydrophone at point i , for a time t_{hi} , before it reaches the hydrophone at point i . The signal then travels through the hydrophone at point i for a time t_{hi} . Thus at the point i , the angle $\theta_i(t)$ at time t is given by Eq. (A4).

$$\theta_i(t) = \omega(t - t_{ei} - t_{hi} - t_i). \quad (A4)$$

For two points i and j one thus observes that $\Delta\theta_{ij}(t)$ is given by Eq. (A5b).

$$\Delta\theta_{ij} = \theta_i(t) - \theta_j(t) = \omega(t - t_{ei} - t_{hi} - t_i) - \omega(t - t_{ej} - t_{hj} - t_j) \quad (A5a)$$

$$\Delta\theta_{ij} = -(\omega t_i - \omega t_j) - \omega(t_{ei} - t_{ej}) - \omega(t_{hi} - t_{hj}) \quad (A5b)$$

The electronic channels to point i and point j were experimentally compared and to a close approximation, it was found that $\omega(t_{ei} - t_{ej}) = 0$. Furthermore, it was temporarily assumed, based on knowledge of the hydrophone design of the two hydrophones, that $\omega(t_{hi} - t_{hj}) = 0$. Under these conditions, Eq. (A5b) becomes Eq. (A5).

$$\Delta\theta_{ij} = -\omega(t_i - t_j). \quad (A5)$$

The travel time to a point i is given by Eq. (A6). Recall that the speed of sound is assumed constant over the test distances.

$$t_i = \frac{R_i}{c} \quad (A6)$$

Use of Eq. (A6) in Eq. (A5) in the next two steps leads to Eq. (A1).

$$\Delta\theta_{ij} = -\omega \frac{R_i}{c} - \frac{R_j}{c}, \quad (A7a)$$

$$\Delta\theta_{ij} = \frac{-\omega(R_i - R_j)}{c}, \quad (A7b)$$

Using Eq.(A2a), one rewrites Eq. (A7b) as Eq. (A1).

For definiteness, the rest of the discussion is in terms of eq. 1 but the discussion also applies in the obvious way to Eq. (A1a). Equation (A1) has a graph of $\Delta\theta_{ij}$ vs f which is a straight line passing through the origin and with a slope, S , given by Eq (A8).

$$S = \frac{-2\pi}{c} [R_i - R_j] \quad . \quad (A8)$$

It is instructive to consider three cases for the slope S , as follows:

Case 1: $S > 0$

The slope will be positive ($S > 0$) if and only if $R_j > R_i$, that is, if point j is farther from the acoustic center than point i . Case 1 is illustrated in Fig. A3a.

Case 2: $S < 0$

The slope will be negative ($S < 0$) if and only if $R_j < R_i$. Case 2 is also illustrated in Fig. A3a.

Case 3: $S = 0$

The slope will be zero ($S = 0$) if and only if $R_j = R_i$, that is, if points i and j are equidistant from the acoustic center. The graph for Case 3a coincides with the horizontal axis since $\Delta\theta_{ij} = 0$ for all frequencies f .

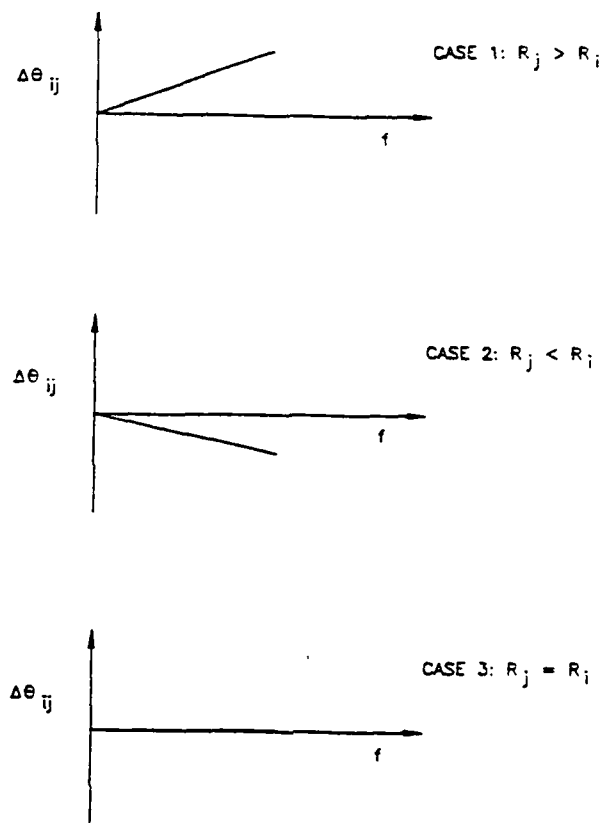


Fig. A3 - Effect of phase slope on relative distances between projector and hydrophone.

In the second IVI tests (January 1988), Cases 1 and 2 were utilized to ultimately adjust for Case 3, that is, to make $R_j = R_i$. This was done as follows. First, at some fixed frequency the hydrophone at point j was moved back and forth relative to the acoustic center until $\Delta\theta_{ij} = 0$. If $\Delta\theta_{ij}$ was found to be greater than 0 (i.e., if $\Delta\theta_{ij} > 0$) then the hydrophone j was moved closer to the acoustic center (i.e., R_j was made smaller) but if $\Delta\theta_{ij} < 0$ then R_j was made larger. At the IVI frequencies a movement of as little as 1 in. was detectable as a change in $\Delta\theta_{ij}$. Once $\Delta\theta_{ij}$ was made equal to zero at a given frequency, then a complete frequency sweep was recorded to verify that the slope, S , was approximately equal to zero and thus, that $\Delta\theta_{ij} = 0$ for all frequencies f of interest for the IVI projector. If this was approximately true, then it was reasonable to assume that any instrumentation errors in measuring $\Delta\theta_{ij}$, could be ignored. A plot of the results of the initial attempt at such an adjustment of R_j is shown in Fig. A4. For convenience, call this Experiment A. Experiment A corresponds to the geometry indicated in Fig. A2 in

which hydrophone i is along the vertical axis. Figure A4 shows that, as desired, $\Delta\theta_{ij}$ is very nearly zero over the entire frequency range. Thus it must be true that $R_i = R_j$. Figure A5 shows that in dB, hydrophone i reading minus hydrophone j reading is about 0.5 dB. At this stage, one did not know if this 0.5 dB difference was due to differences in hydrophone sensitivity and channel gain or actual pressure differences due to a non-omni vertical pattern. The two-step process, described next, solved this problem.

The use made of the $\Delta\theta_{ij} = 0$ method was a two-step process as follows. At Step 1 in the process, Hydrophone j was positioned along the vertical axis as close to hydrophone i as practical as illustrated in Fig. A6. R_j was adjusted until $\Delta\theta_{ij} = 0$ so that $R_j = R_i$. Both hydrophone readings were recorded and any differences in the corresponding measured pressures was attributed either to differences in the hydrophone sensitivity or to differences in the instrumentation channel gains. Next for Step 2, hydrophone j was moved to a position in the horizontal plane as shown in Fig. A2. R_j was again adjusted until $\Delta\theta_{ij} = 0$ so that $R_j = R_i$. If the difference in the two hydrophone readings at Step 2 was the same as for Step 1, then the pressure in the vertical and horizontal directions were shown to be the same; if not, then some directivity was present. Since the difference in the reading at Step 2 and Step 1 were essentially the same and the difference in channel gains was negligible, it was thus shown that the above indicated bias was due to experimental error, not vertical directivity of the IVI source.

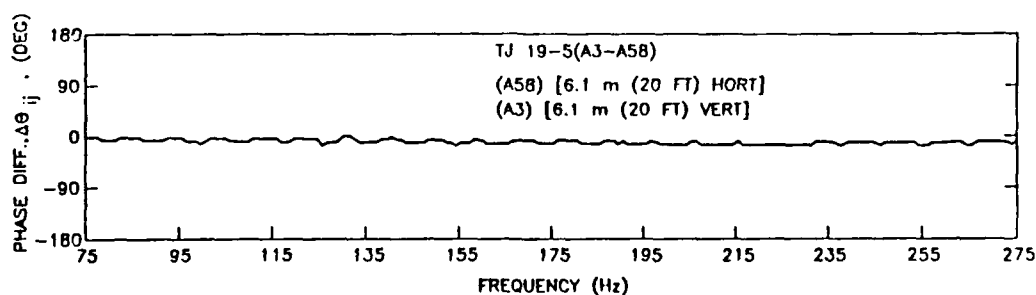


Fig. A4 - Phase difference sensed by hydrophones in the horizontal and vertical planes of projector (Experiment A: adjusting R_j to obtain $\Delta\theta_{ij} = 0$).

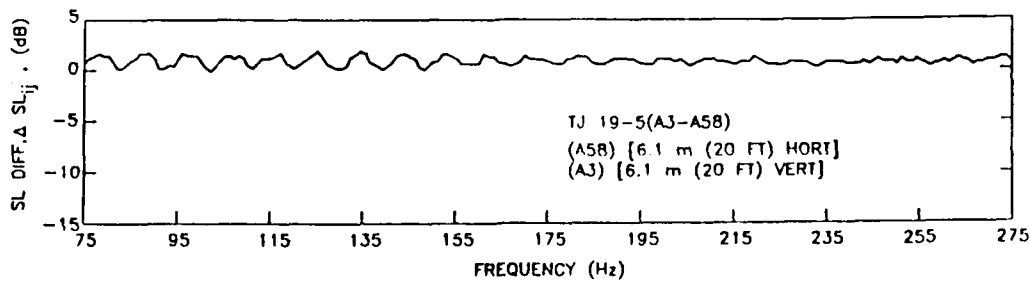


Fig. A5 - Source level difference sensed by hydrophones in the horizontal and vertical planes of projectors (Experiment A).

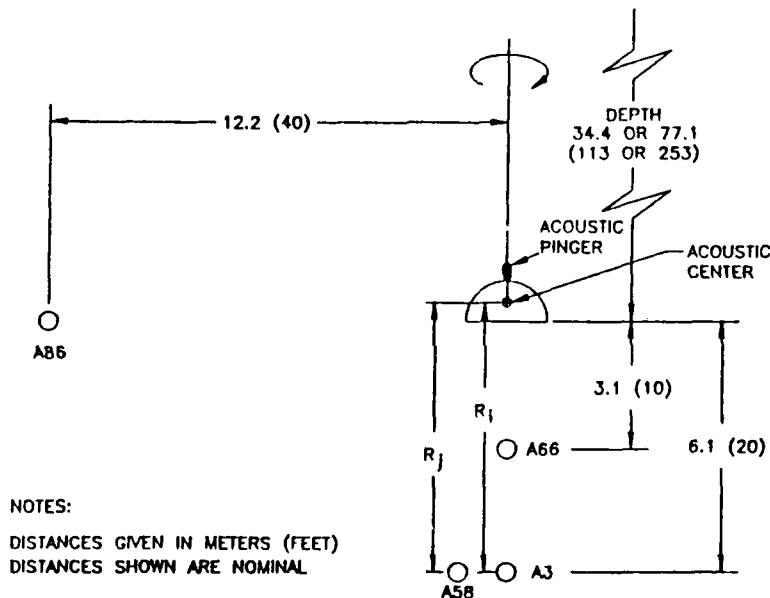


Fig. A6 - Test setup for Step 1.

An additional benefit was gained from this two step procedure. For practical reasons, it was easier to measure the horizontal distance from the acoustic center, R_j , shown in Fig. A2 than the vertical distance R_i . First of all the acoustic center was known to lie somewhere on the vertical axis (recall that the horizontal patterns were known to be omni about the vertical axis), but it was not obvious where the acoustic center was located along this vertical axis. Secondly, the actual distance R_j from the vertical axis could be measured two ways, with a ruler (distance between vertical axis pipe and cable suspending hydrophone j) and with an acoustic pinger located as shown (Fig. A2) on the vertical axis. In general, it may be advantageous in some future experiments to deliberately locate a hydrophone, j , such that R_j is easily measured and then use the $\Delta\theta_{ij}$ method to keep track of the distance R_i for some second hydrophone, i . In particular note from Eq. (A1), if the slope, S , is measured (and of

course the speed of sound) then $R_i - R_j$ may be calculated. If R_j is measurable then R_i may also be calculated.

Some actual plots of application of this two-step $\Delta\theta_{ij}$ method are presented next to show the degree to which the differences in the hydrophones reading of Steps 1 and 2 were nearly the same thus verifying that the subject bias was indeed experimental error. In the actual series of IVI experiments the initial application of the $\Delta\theta_{ij} = 0$ method to make $R_i = R_j$ occurred in Experiment A described above. Experiment-A had the geometry of Step 2 of the complete two-step process. Therefore, the first complete application of the two-step process was carried out as follows. From Experiment A one proceeded to Step 1. Hydrophone i was not moved but hydrophone j was moved close to hydrophone i as indicated in Fig. A6. Figure A7 shows that in Step 1 $\Delta\theta_{ij} = 0$ was achieved to a good approximation so that $R_i = R_j$ for Step 1. Figure A8 shows that at Step 1, the difference in the hydrophone/channel readings was about 0.5 dB. Next, in Step 2 one attempted to use the $\Delta\theta_{ij} = 0$ method to return hydrophone j to the same position it occupied in Experiment A. Hydrophone i was again left undisturbed. Figure A9 shows that in Step 2, $\Delta\theta_{ij} = 0$ was again achieved to a good approximation over the frequency band. Figure A10 shows the difference in the hydrophone/channel reading to again be about 0.5 dB. Since Steps 1 and 2 yielded essentially the same difference in hydrophone/channel readings it was concluded that the pressure amplitudes were the same at points i and j and thus that the IVI projector was omni in a vertical plane.

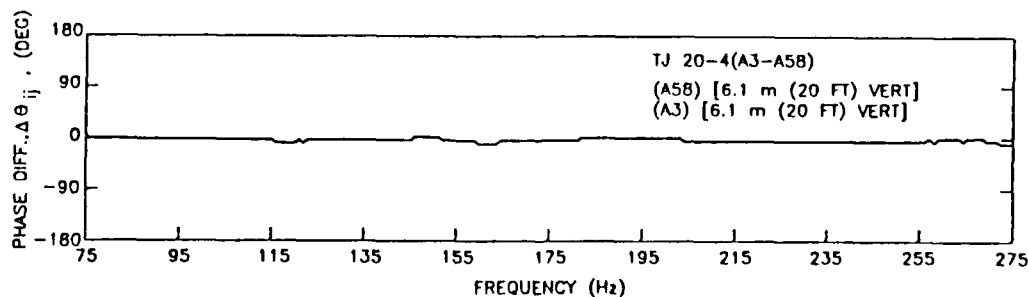


Fig. A7 - Phase difference sensed by hydrophones in the vertical plane of projector (Step 1: adjusting R_j to obtain $\Delta\theta_{ij} = 0$).

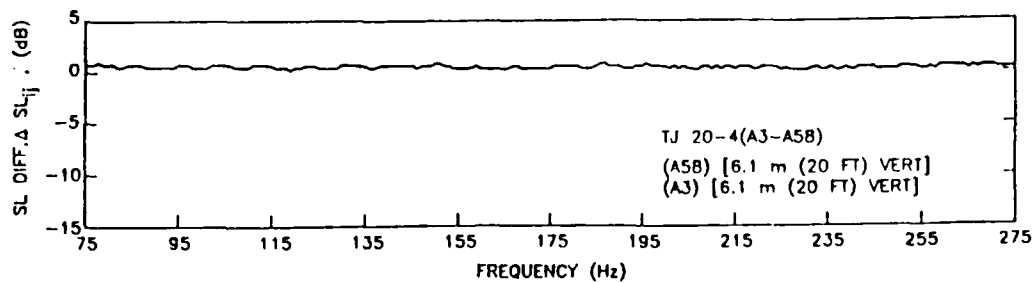


Fig. A8 - Source level difference sensed by hydrophone in the vertical plane of projector (Step 1).

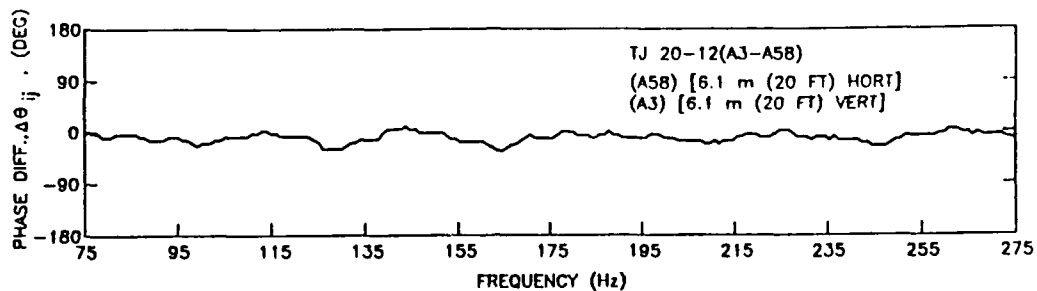


Fig. A9 - Phase difference sensed by hydrophones in the horizontal and vertical planes of projector (Step 2: adjusting R_j to obtain $\Delta\theta_{ij} = 0$).

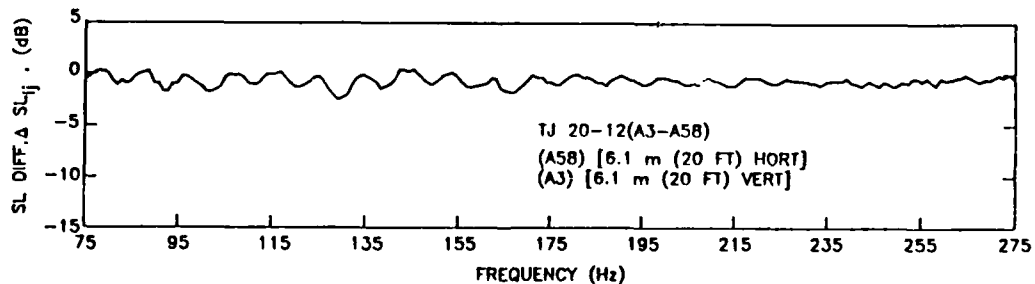


Fig. A10 - Source level difference sensed by hydrophones in the horizontal and vertical planes of projector (Step 2).

In addition, Step 2 gave the same data as Experiment A showing that one had in fact succeeded in repositioning hydrophone j to the same value of R_j in Step 2 as had occurred in Experiment A. Figure A11 shows another way to demonstrate this last point. In Fig. A11, the reading of hydrophone j during Experiment A and at Step 2 are presented and shown to agree in many of the detailed variations vs frequency.

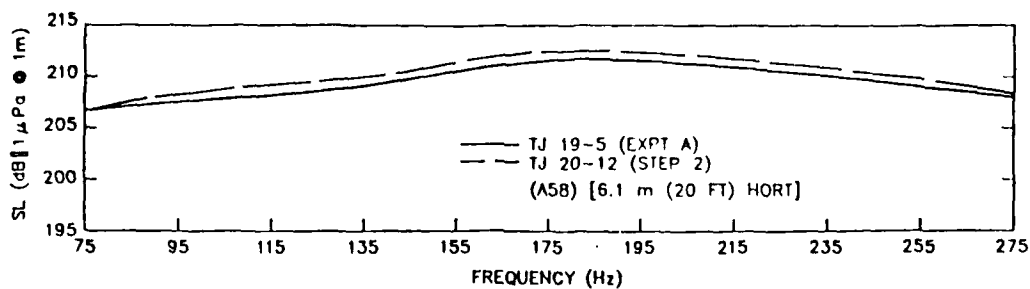


Fig. A11 - Comparison of source level by hydrophones in the horizontal plane of projector (Experiment A and Step 2).

After completion of verification that the 1-dB bias was indeed instrumentation error it was also clear that the most accurate position measurement was for a hydrophone in the horizontal plane such as that positioned at point j in Fig. A2. Also, the calibration of this hydrophone was recent and of good quality. Therefore, the readings from the hydrophone in position j in Fig. A2 were used to produce the most definitive data of source level vs frequency as shown in Fig. A12. The data for Fig. A12 source level was produced with a hydraulic system pressure of 20.7 MPa (3000 psi) to IVI Projector No. 1. The low level drive signal was set at 10.2 dB.

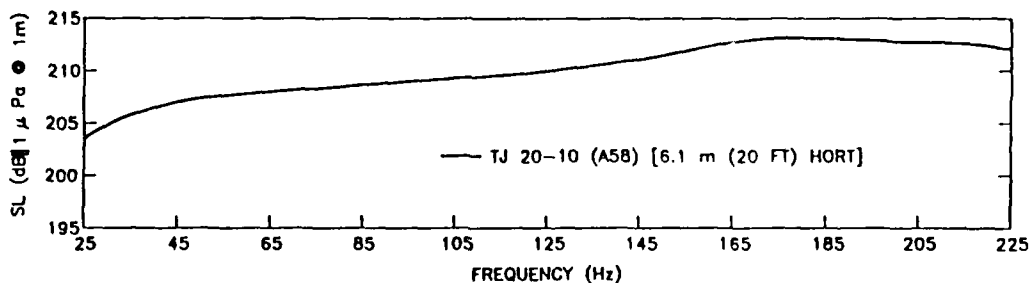


Fig. A12 - Source level of Projector No. 1.

It was temporarily assumed above that the phase shift was the same through both hydrophones (that is the hydrophone at point i and the hydrophone at point j). The experimental fact that the plot of $\Delta\theta_{ij}$ did indeed turn out to be approximately a straight line passing through the origin was taken as on the spot justification for this assumption. Had use of the $\Delta\theta_{ij}$ method been planned in advances the assumption would have been experimentally verified for the subject hydrophones.

APPENDIX B
TEST SUMMARIES

TABLE B1: Projector No. 1 Test Summary

TEST TJ	CHART No.	DRIVE SIGNAL (dB)	FREQ RANGE (Hz)	CHANNEL		COMMENTS
				A	B	
15-5	1,2	--	25-225	A45	A86	Manual 1-Hz freq. stepping
15-6	3	--	25-225	A45	A86	Anal stepping freq: 2 s 0 ea Hz
15-7	4,5	3.1	25-225	A45	A86	3 s 0 ea. Hz (Used thereafter)
	6,7			DS	LVDT	
15-8	8,9	3.1	25-225	A58	A86	
	10,11			DS	LVDT	
15-10	12,13	3.1	25-225	A66	A86	
	14,15			DS	LVDT	
15-11	16,17	3.1	25-225	A3	A86	
	18,19			DS	LVDT	
15-12	20,21	3.1	75-275	A58	A86	
	22,23			DS	LVDT	
16-1	24,25	3.1	75-275	A58	A86	
	26			DS	LVDT	
16-2	27,28	3.1	75-275	A58	A86	
	29,30			DS	LVDT	
16-3	31,32	3.1	75-275	A58	A86	Projector lowered to 253 ft.
	33,34			DS	LVDT	
16-4	35,36	3.1	25-225	A66	A86	
	37,38			DS	LVDT	
16-5	39,40	3.1	25-225	A3	A86	
	41,42			DS	LVDT	
16-6	43,44	3.1	25-225	A3	A66	Compare w/20-10
	45,46			DS	LVDT	
16-8	47-49	10.2	25-225	A58	A66	No Good
	50,51			DS	LVDT	
16-9	52,53	10.2	75-275	A58	A3	
16-10	54,55	10.2	75-275	A58	A86	

Table B1 continued

TEST TJ	CHART No.	DRIVE SIGNAL (dB)	FREQ RANGE (Hz)	CHANNEL		COMMENTS
				A	B	
19-2	57,58	10.2	75-275	A58	A3	
	59,60			DS	LVDT	
19-3	61,62	10.2	75-275	A3	A58	
	63,64			DS	LVDT	
19-5	65,66	10.2	75-275	A3	A58	Compare w/20-3
	67,68			DS	LVDT	
19-7	69,70	10.2	75-275	A66	A58	Compare w/20-2
	71,72			DS	LVDT	No Good
20-1	73,74	--	25-225	G _A	G _B	System Gain Check
20-2	75,76	10.2	75-275	A66	A58	Compare w/19-7
	77,78			DS	LVDT	
20-3	79,80	10.2	75-275	A3	A58	Compare w/19-5
	81,82			DS	LVDT	
20-4	83,84	10.2	75-275	A3	A58	
	85,86			DS	LVDT	
20-5	87,88	10.2	25-225	A3	A58	
	89,90			DS	LVDT	
20-6	91,92	10.2	25-225	A86	A58	
	93,94			DS	LVDT	
20-7	95,96	10.2	25-225	A86	A58	Compare Charts 96 & 99
	97,98			DS	LVDT	
20-8	99	--	25-225	A86	A58	Periodic noise driving vibrator
20-10	100,101	10.2	25-225	A3	A58	Compare w/16-6
	102,103			DS	LVDT	
20-11	104,105	10.2	25-225	A3	A58	
	106,107			DS	NF	
20-12	108,109	10.2	75-275	A3	A58	
	110,111			DS	NF	

NOTES:

Tests TJ15-5 through TJ16-2 were conducted at a depth of 113 ft.

Tests TJ16-3 through TJ20-12 conducted at 253 ft. depth.

LVDT is linear variable differential transformer.

DS is drive signal of vibrator.

NF is nearfield hydrophone of vibrator.

TABLE B2 - Dual-Projector Module Test Summary

TEST TJ	CHART No.	DRIVE SIGNAL (dB)	FREQ RANGE (Hz)	CHANNEL		COMMENTS
				A	B	
22-1	112,113	3.1	25-225	L1	L2	Vibrators operated in air (#1 & #2)
	114,115			DS1	DS2	
22-2	116,117	-1.0	25-225	L1	L2	93 ft depth for rest of tests (#1 & #2)
	118,119			DS1	DS2	
22-3	120,121	3.1	25-225	L1	L2	#1 & #2
	122,123			DS1	DS2	
23-1	124,125	--	25-225	G _A	G _B	System Gain Check
23-2	126,127	3.1	25-225	A58	A86	#1 only
	128,129			DS1	L1	
23-3	130,131	3.1	25-225	A58	A86	#1 only
	132,133			DS1	L1	
23-4	134,135	3.1	25-225	A58	A86	#1 & #2
	136,137			L1	L2	
23-5	138,139	3.1	25-225	A58	A86	#1 & #2 free-running
	140,141			L1	L2	
23-6	142,143	3.1	25-225	A58	A86	#1 & #2 free-running
	144,145			DS1	DS2	
23-7	146,147	10.2	75-275	A58	A86	#1 only
	148,149			L1	NF1	
23-8	150,151	10.2	75-275	A58	A86	#1 only
	152,153			L1	NF1	
23-9	154,155	3.1	25-225	A58	A86	#1 & #2
	156,157			L1	L2	
23-10	158a	3.1	100	--	--	#1 & #2 Pattern w/A58 @ 50 ft (No Good)
23-11	158b	3.1	100	--	--	#1 & #2 Pattern w/A58 varying (No Good)
25-1	159a,b	10.1	75-275	L1	L2	#1 only (#2 charged), see note 8

Table B2 continued

TEST TJ	CHART No.	DRIVE SIGNAL (dB)	FREQ RANGE (Hz)	CHANNEL		COMMENTS
				A	B	
25-2	160,161 162,163	10.2	75-275	A58 L1	A86 L2	#1 only (#2 charged), see note 8
25-4	164	3.1	100			#1 & #2 Pattern w/A58 @ 71 ft Phase diff. 110° or 117°
25-5	165	3.1	100			#1 & #2 Pattern w/A58 @ 71 ft Green curve $\eta=0^\circ$ Red curve $\eta=90^\circ$
25-6	166,167 168,169	3.1	75-275	A58 DS1	A86 L1	Hydraulic pressure = 3800 psi

NOTES:

All tests conducted at 93 ft depth.

L1, L2 is linear variable differential transformer for Projectors 1 and 2.

DS1, DS2 is drive signal for Projectors 1 and 2.

NF1 is nearfield hydrophone for Projector No. 1.

For tests TJ 22-1 through TJ 23-11, involving two projectors operating simultaneously, the 20° drive signal phase compensation was not employed; i.e., for these tests $\eta = -20^\circ$ rather than $\eta = 0^\circ$.

In test TJ 25-4 there was uncertainty about the value of the phase difference ($\eta = 110^\circ$ or 117°). A phase of 117° fit the simple theory better.

In test TJ 25-5 the 20° drive signal phase compensation was used so the phase difference between the projector surfaces was either 0° or 90° .

In tests TJ 25-1 and TJ 25-2, Projector No. 1 was operating normally.

Projector No. 2 was charged at system hydraulic pressure with the centering feedback loop and air compensation system functioning, but the acoustic piston was not driven.